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THE EFFECTS OF LEAD-TIME AND INVENTORY ON LABOR PRODUCTIVITY

A Thesis in

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by

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ABSTRACT

This thesis quantifies several important theories of lean construction. It presents a relationship between lead-times, inventory, and labor productivity with regards to highway bridge construction. This research is restricted to formwork and concrete placement. Four case study projects are introduced and evaluated. Factors that effect labor productivity are identified. A relationship between lead-time, crew size, and inventory is established. Furthermore, two tools are presented to help managers plan projects by determining work expectations, crew size, and required inventories of formwork. The case studies are used to demonstrate the potential of these tools.

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CHAPTER 1.

INTRODUCTION

A developing management theory in the construction industry is lean thinking, better known as lean construction. The main objective of lean construction is the elimination of waste in the construction process. The purpose of this thesis is to quantify the size of lead-times and inventories that are required in order to achieve good performance in terms of daily productivity on a project.

Background

Lean construction stems from the lean production systems originally introduced in the Japanese auto industry. Developed by Taiichi Ohno for Toyota, lean production or just-in-time production systems shorten the time between product order and delivery. Further, lean production attempts to reduce the time line by eliminating non-value-waste and improving workflow. (Ohno, 1978)

There are two basic ways of improving workflow. The first way is to reduce or eliminate variability. Simply, there must always be a consistent amount of input resources available in order to produce a consistent amount of output. Moreover, this consistency must remain in place throughout each step of the production process.

The second way of improving workflow is to create a lead-time between each step of the production process. Lead-time is a period of time required between each step.

Lead-time provides production managers flexibility to react to variability in resources. Lead-time should allow a consistent amount of work to be available despite changes in output from the preceding steps.

Directly related to lead-time is the concept of inventory. Inventory is defined as any material or work in progress not immediately needed by the subsequent production step. For example, formwork erected awaiting concrete placement is an example of inventory. The time between when formwork was erected and concrete placed is an example of lead-time. This example is illustrated in Figure 1.1 that depicts the inventory and lead-time at time *i*. Formwork on a construction site that will not be immediately used is another example of inventory.

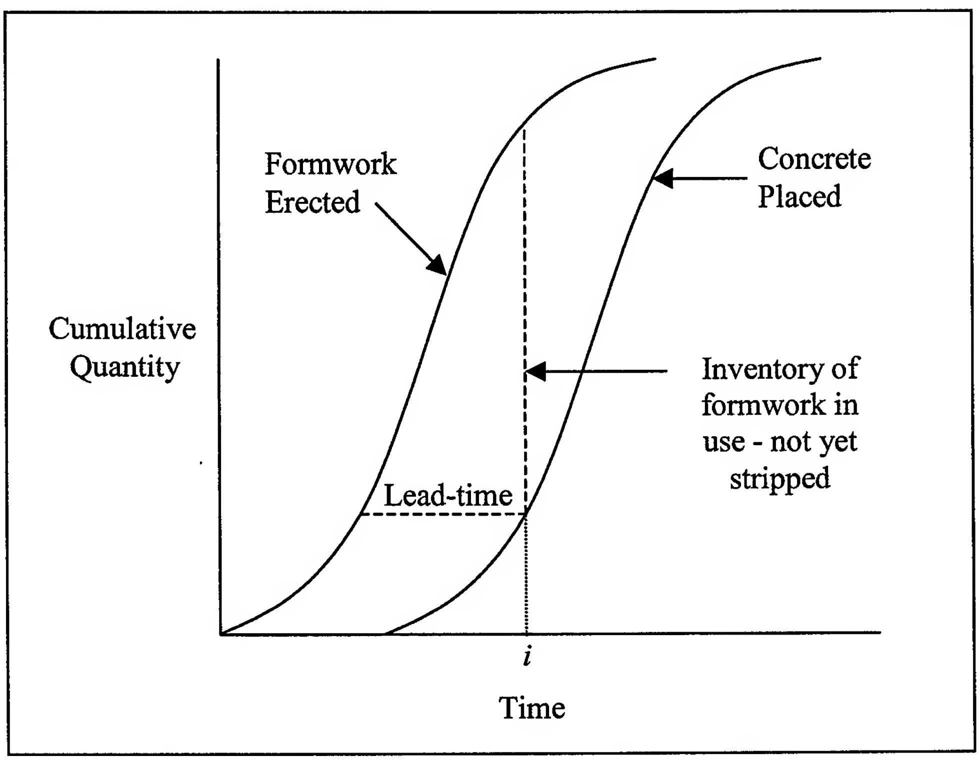

Figure 1.1 Lead-time – Inventory Illustration

Lead-time allows an inventory to be created. Lead-time and inventory are related, more lead-time, more inventory. Like lead-time, inventory should allow a consistent amount of input resources available despite changes in the output of the preceding step. Lead-time and inventory reduce the effects of variations in the flow of resources and allows flexibility in the choice of work. (Tommelein, 1998) When management tries to minimize variability, it can result in reduced lead-times. In construction, one must define the right amount of lead-time.

As stated previously, lean construction looks to eliminate all waste in the construction process. Lead-time and inventory are considered waste using the just-in-time delivery system. With just-in-time delivery, a later process will pull only the quantities of items as they are needed from the preceding process. (Ohno, 1978) Tommelein and Yi Li state that the objective of just-in-time is to supply the right materials at the right time at every step of the process. They further state that traditional push systems increase waste because they are based on estimates and include factors to compensate for uncertainty. (Tommelein and Yi Li, 1999)

Statement of the Problem

Correctly, applying the concepts of lean production to construction is a significant challenge. There are considerable differences between a manufacturing plant and a construction project. Koskela lists three characteristics that distinguish construction: the one-of-a-kind nature of projects, site production, and temporary conglomerate organizations. (Ballard and Howelll, 1998) Ballard and Howelll further state that construction possesses two unique identifying characteristics: 1)"fixed position

manufacturing", and 2) they are rooted in place. Fixed position manufacturing means the production stations or crews move through the emerging product instead of the product moving through an assembly line. Rooted in place means they are subject to the environmental conditions that surround the project. These conditions can be natural, such as soil conditions, or artificial, such as building codes. (Ballard and Howelll, 1998) As a result of these distinctions, lean production systems cannot be strictly applied to construction.

Lean theory reduces lead-time and inventory to as small as possible since they are defined as waste. Lean production strives to reduce variability in workflow in order to accomplish this elimination of waste. However, the dynamic and fluid nature of construction demands that inventories and lead-time be maintained in order accommodate variability. To date, the length of lead-time and size of inventories required in construction have not been quantified. Moreover, little research has been done on how lead-time and inventory affect productivity on construction projects. Furthermore, research in this area of lean construction has been largely theoretical. Little has been written in the literature showing data to support the theory.

Objective

The purpose of this thesis is to determine the relationship between lead-time, inventory and daily productivity regarding formwork on highway bridge construction. To accomplish this, it is essential to answer a number of questions. First, what are the significant factors that affect productivity on this type of construction work? What is the

relationship between inventory and lead_time, and how is it best expressed? Next, what is the three-way relationship between lead-time, inventory and productivity? Finally, how does the type of work and the forming system affect this three-way relationship?

Definitions of Key Terms

The following terms are defined below, as they will be used in this thesis.

Lead-time - The amount of time (in days) that erection of formwork precedes stripping based on percent of work complete. Lead-time is graphically represented in Figure 1.1 as the horizontal distance, b_i, between the progression curves at any given percent complete.

Inventory - The quantity of formwork available to be erected. This is the unused portion of the total quantity of formwork available at a project. Included in this value is formwork ready to be erected even when the work area is not available. The inventory can be calculated using the following equation:

$$I_i = T - x_i$$

Where: I_i = inventory at the end of day i

T = total quantity of formwork on site

x_i = quantity of formwork in use at the end of day i. The quantity of formwork in use is depicted in Figure 1.1 as the vertical distance between the progression curves on any work day.

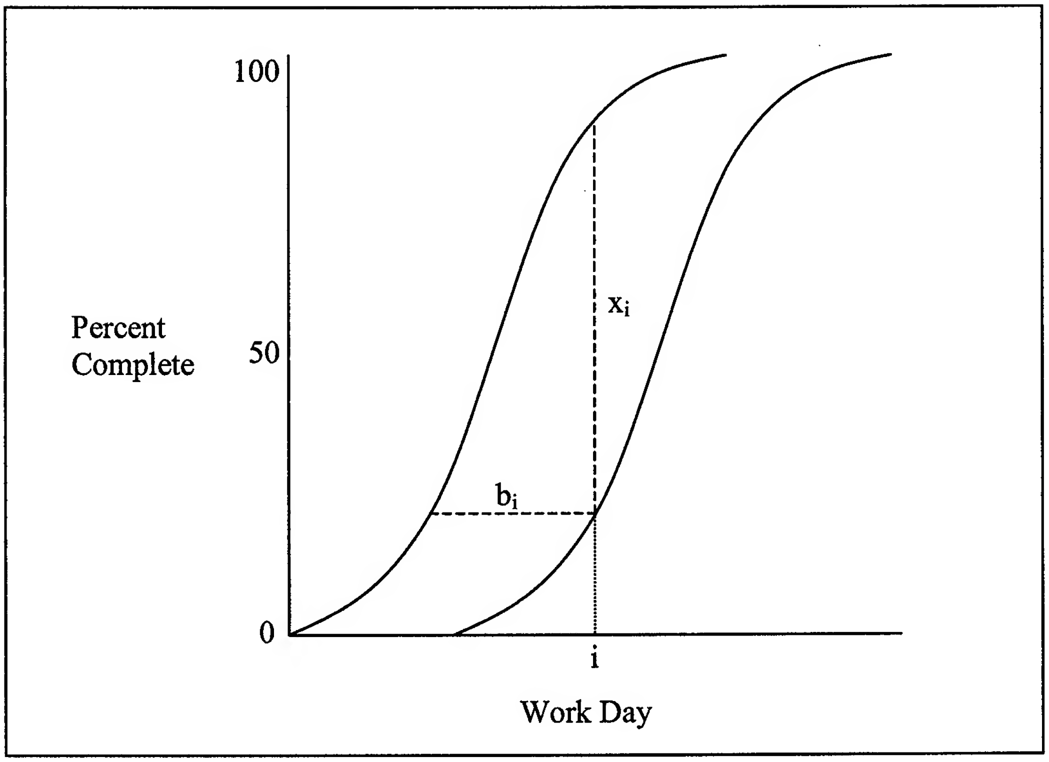

Figure 1.2 Progression Curve

Productivity - Work-hours required to erect, plumb and strip a square foot of formwork.

$$\text{Productivity} = \frac{\text{Workhours Expended}}{\text{Quantity of Work Completed}}$$

Literature Review

The focus of the literature review is on the topics of lead-times, inventory, and lean construction principles. The review discusses the background of lean production, variability in workflow, and ways to reduce variability.

Background

The Toyota Production System is viewed as the model for what is now termed as lean production. Taiichi Ohno, Executive Managing Director, originally developed the just-in-time production system for Toyota. The focus of the Toyota Production System is the complete elimination of waste. Paramount to the elimination of waste is improvement of workflow. Ohno describes the meaning of just-in-time production, as a later process getting only what it needs from an earlier process. The earlier process then produces another item of what the latter process just took. The later processes picking up materials from earlier ones establish a pull system. (Ohno, 1978) Just-in-time is a system that starts by identifying the final product then works backwards through the production chain to pull the needed materials.

Communication is a critical part of just-in-time theory. Toyota uses a slip of paper called a *kanban* for this information flow. The *kanban* passes information on production and pick up / transport. Further the *kanban* is used to prevent overproduction, excessive transport, and maintain inventory control. (Ohno, 1978)

The practice of just-in-time delivery has been evident in the construction industry for years with regards to concrete delivery. Tommelein and Li describe concrete batching and delivery as a lean system. They correctly point out that two-way communication between the concrete vendor and customer is the cornerstone in this pull system. The primary need for communication is due to variability in the workflow and unforeseen circumstances that make forecasting deliveries difficult. Additionally, they point out that communication must continue not only through the planning phase, but also during production. (Tommelein and Li, 1999)

Variability in Workflow

Reliable workflow is the key component of lean construction. Variability in workflow ultimately leads to waste. Thomas explains that workflow follows a predictable pattern. During bulk installation, workflow increases at a steady rate and peaks between 50 to 85% then steadily declines as systems are completed. Thomas further explains that when work is unavailable in a consistent manner, inefficiencies occur. (Thomas, 1999)

The impact of unreliable workflow between trades can be easily modeled. Tommelein, Riley, and Howell describe one such model, The Parade Game. The model uses random number generators with different degrees of variability to determine the units of daily output produced by each step in a production process. The model demonstrates it is possible to reduce waste and shorten project duration by improving workflow between trades. The Parade Game also demonstrates that constant output or

reduced variability will shorten the overall duration of the project and improve performance of succeeding trades. Furthermore, playing the game using greater variability may increase your chances of finishing the project early, but it also increases your chances of finishing late. Ultimately, it is essential that work be released consistently between trades to minimize waste and shorten project duration. (Tommelein, Riley, and Howell, 1998)

Reducing variability in workflow is a difficult task. Numerous environmental factors affect construction projects on a daily basis. Most construction projects do not occur in a controlled environment and are exposed to four major causes of variability. These factors are work availability, materials, equipment, and weather. "Installation crews and equipment are often kept waiting because of delays in materials supply and delays in completing prerequisite site work." (Tommelein, 1998) Thus, management's ability to react to variability is limited to how they utilize labor.

Improving Workflow

One aspect of lean construction attempts to deal with variability by shielding work crews. Shielding is the process of protecting the crew and their work plan by making assignments that can be accomplished. This process ensures that all material, equipment, and work is available. Further, it ensures no changes will be made once the assignment is given to the crew. Typical percent plan complete for unshielded crews is between 30 to 60%. The process of shielding tends to bring the percent plan complete up to 70%. (Ballard, 1999)

Ballard suggests four ways to improve workflow and raise the percent plan complete above 70%. The first technique is for crew planners to refuse the assignment or "just say no." The second technique calls for an improvement to activity definition models that decompose tasks allowing planners to ensure everything is ready prior to assigning the task. Next, cause analysis must be conducted on every failed assignment. The intent of the cause analysis is to determine the root cause for the task not being completed and learn from that mistake. Finally, a sizing criterion for assignments should be applied. This means not loading a crew at 100% capacity. Loading a crew or production unit at 100% is the norm, but the work environment and variability doesn't allow 100% to be accomplished. Ballard suggest that applying the sizing criterion will improve the reliability of workflow between trades and/or crews. The sizing criterion reduces the quantity of work planned and expected to be completed by a crew. The sizing criterion will also decrease the productivity of the first trade, but should improve all subsequent trades. (Ballard, 1999) The key component of this concept is that a steady flow of work will be available throughout the entire production process.

Another strategy that can be employed to combat variability is the use of multi-skilled workers. Multi-skilled workers possess a range of skills that allow them to be used in more than one trade. Additionally, these workers can be used flexibly on a project or easily moved within an organization. (Burleson, et al., 1998) Mecca states that multi-skilled labor helps eliminate risk points of variability in workflow, the number of workers, and the total number of sequences required to complete a project. (Mecca, 1999)

The uncertainty of the timing and delivery of work from one activity to another is a significant management problem. "Lacking tools to minimize uncertainty in these flows, managers strive for flexibility so the project can proceed in the face of erratic deliveries and unexpected problems." (Tommelein, 1998) The flexibility most managers adopt is the use of lead-times. Lead-times help managers deal with variation in workflow and optimize labor and equipment utilization. A lead-time allows an inventory of work to be readily available to subsequent craftsmen. However, this may lead to individual processes having a good productivity, but total production taking much longer, potentially increasing cost and project duration. Therefore, lead-times must be strategically located and sized. (Tommelein and Weissenberger, 1999)

The sizing of lead-times is an uncertain task and must be done with careful consideration. When deciding on size and placement of a lead-time, one must weight the overhead cost associated with a longer project against the potential savings in labor cost. Ideally, lead-times should be sized at the minimal amount of time that will maximize labor productivity.

Summary

The research focuses on variability and ways to improve workflow. A number of ways to improve workflow includes the use of: a sizing criterion, multi-skilled crews, and lead-times. Each of these techniques can ultimately lead to better productivity being achieved on a project. However, given the current construction practices in the United States, the most readily applicable technique is the use of lead-times.

A review of the literature identifies the need to pursue a line of research to quantify the use of lead-times for the improvement of productivity. The majority of the reviewed literature dealing with lean construction, more specifically lead-times and inventory, is conceptually based. While much has been written on this topic, little is quantified with actual data. There is a need to develop techniques to help contractors plan and size lead-times and inventories.

Value of Research

The conclusions developed during this research will allow contractors to reduce variations in workflow through strategic use of lead-times and inventories. This research will quantify the level of lead-times and inventories required to optimize labor productivity. Additionally, the conclusions developed can be used as planning tools when determining crew sizes and work expectations. Finally, this information will allow contractors to make significant cost savings on similar projects.

Methodology

There were a number of steps required to complete this thesis. The first step was to conduct a review of the literature, the results of which were previously discussed. Field data on four bridge construction projects was collected over a period of six months. The duration and size of each project was different. Use of these four projects, provided 179 workdays to be analyzed. The data sets were then processed to determine

performance parameters, lead-times, and inventories. Using this information, relationships were then developed and analyzed.

Collection of Field Data

Data Source.

Data were collected from the on going expansion of Interstate 99 from Bald Eagle to Interstate 80 in Pennsylvania. Data were collected from four different highway bridge construction sites in the State College / Pleasant Gap area. The data also reflect two contractors, each managing two projects.

Data Collection.

Data were collected on quantities of labor input and production output. The labor input was simply measured as the total quantity of hours worked daily. Total work hours were the sum of the hours each craftsman worked daily. For example, if 5 craftsmen worked for 10 hours on a task, then the daily total was 50 work hours.

Output was measured on the three major tasks associated with construction of the bridge piers and abutments. These tasks were formwork, reinforcing steel, and placement of concrete. Data on formwork included the daily quantities that were erected, plumbed, and stripped. These quantities were easily visible and measurable.

Steel reinforcing was measured in terms of tons erected. This was accomplished in two steps. First, a material takeoff for each section of the bridge was accomplished (i.e. footer, pier, pier caps). Data collection on site noted the section of the bridge being worked upon as well as an estimate of percent completed (daily and overall). The quantity of steel reinforcing erected that day was then calculated from the material takeoffs based upon the daily percent complete. This procedure was required based upon the difficulty in determining the tonnage of steel erected and the unreliability of foreman estimates. Finally, concrete placement was measured as the quantity of cubic yards placed. These data were collected from the foreman on site whenever possible and confirmed against the design drawings. Data were collected on these structures from start to finish including footings, walls, piers, and pier caps.

A daily journal of activities on site was also kept. This journal included the date and time of observations, locations and activities of the respective crews; problems encountered by each crew, notes on materials and equipment, significant weather events and other general observations.

Organization of Thesis

This thesis is organized into three parts. The first part is an analysis of the projects and the data sets. It describes each of the projects in detail including the workforce organization and inventory of formwork. It also introduces the lead-time-inventory relationship. The second part evaluates each of the projects based upon their performance parameters. This part describes how the data were processed and evaluated.

It also provides a cause-effect analysis on each of the projects demonstrating the affect management has on a project. This section concludes with the development of a tool that contractors can use to develop crew work expectations. The third part describes the relationships between lead-time, inventory, and productivity. It concludes with development of a tool that will allow contractors to appropriately balance lead-time, inventory, and crew size.

CHAPTER 2

DISCRIPTION OF THE PROJECTS AND DATA SETS

The five projects studied are part of the Interstate 99 / Route 26 Relocation Project in Centre County, PA. This overall project includes the construction of a new eight mile, four lane, limited access highway. The overall estimated cost of the project is $192M. Figure 2.1 shows the general area of construction. Figure 2.2 is a blow up of the construction area.

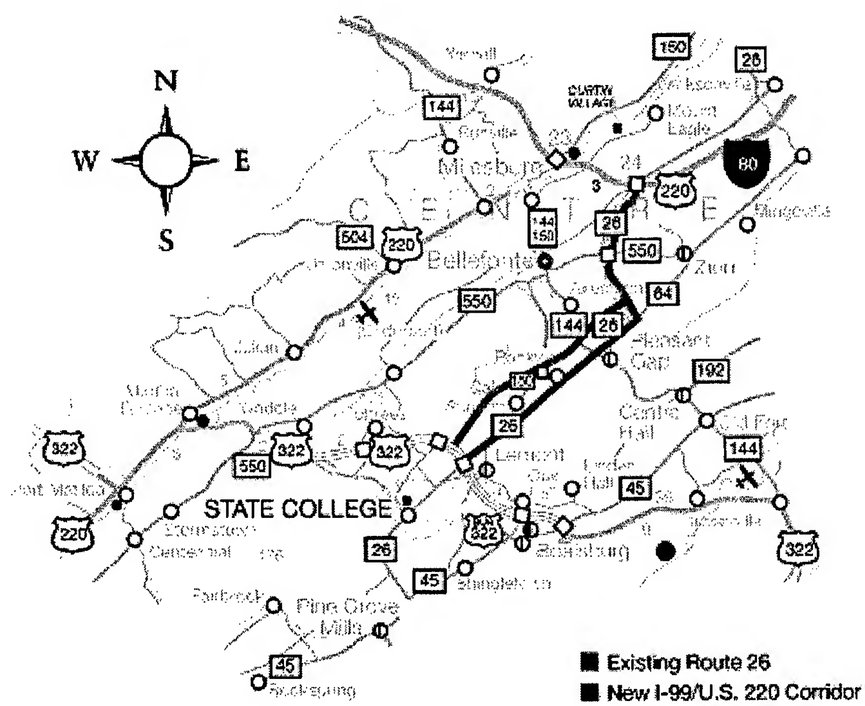

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Figure 2.1 Location of New I-99 Construction

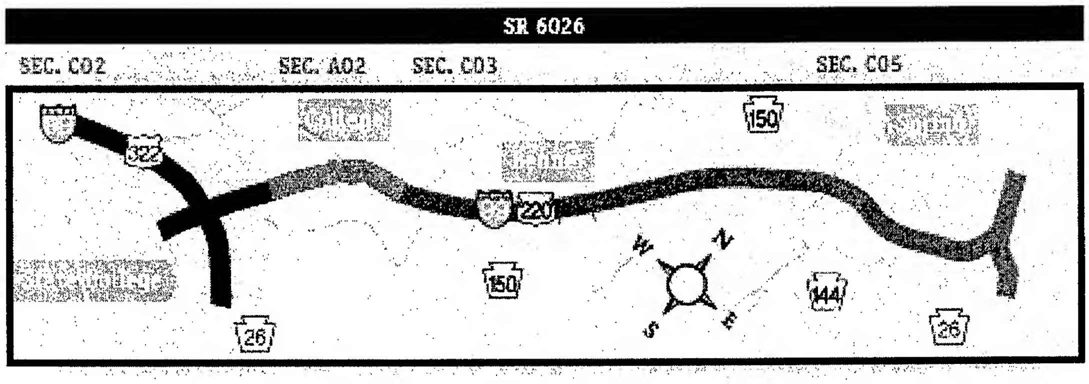

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Figure 2.2 I-99 Construction Area

Projects

Logan Branch

The Logan Branch project consists of two similar four span bridges located over State Route 144 and Logan Branch Creek, and are being built by Contractor A. (Bridge Structure #22487 and Bridge Structure #22488) The total span of the bridges is 920 feet. With a width of 43 feet, each bridge will support one-way traffic. The bridges have a 1°, 15' degree of curvature and are super-elevated. The bridges will consist of a concrete deck supported by steel plate girders. The girders are connected to cast in place, reinforced concrete piers. Both bridges are identical in those regards. The only difference between the bridges is the subsurface support. All pier footings are supported by steel H-piles. However, bridge structure #22488 has one footing that is supported by both H-piles and drilled pipe piles due to soil conditions under that footing. Additionally,

the maximum working height above ground level is 107 feet. Figure 2.3 is a picture of the project site. The estimated cost of the bridges is $8.094M.

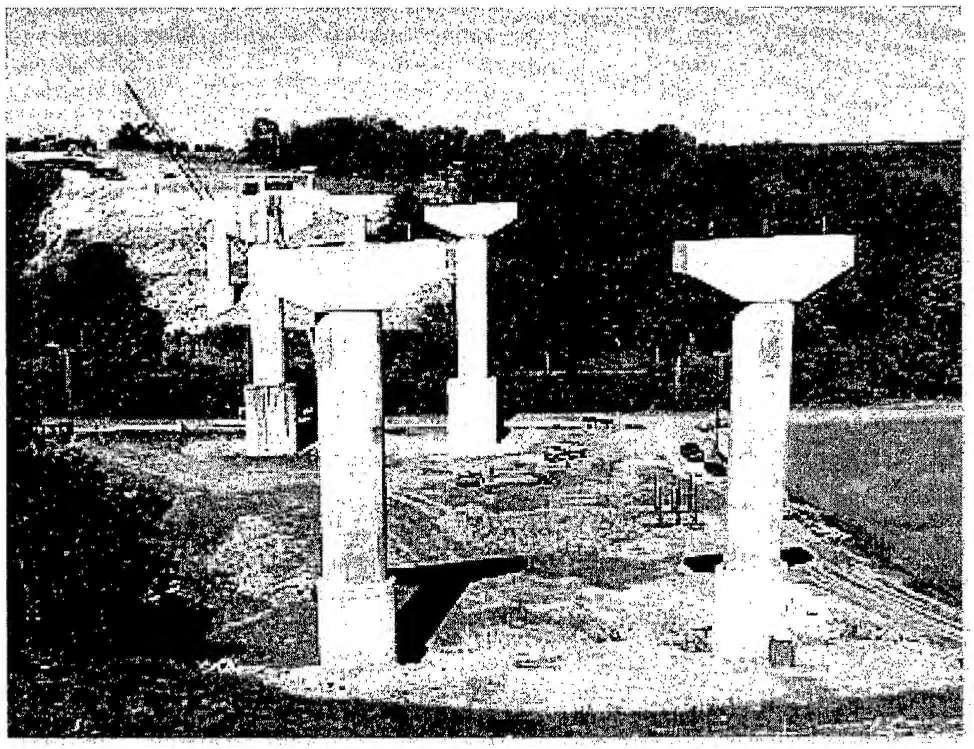

Figure 2.3 Logan Branch Bridge

Weaver Hill

The Weaver Hill project is also being built by Contractor A. (Bridge Structure # 22491) This project is a two lane, single span bridge. The Weaver Hill Bridge has a span of 140 feet and a width of 52 feet. This bridge consists of a concrete deck supported by prefabricated, prestressed concrete beams. The beams are supported and connected to the bridge abutments. The abutments are cast in place concrete and are supported by

steel H-piles. The maximum working height on this structure is 24 feet. The estimated cost of the project is $815K. Figure 2.3 shows the bridge after the concrete beams have been placed.

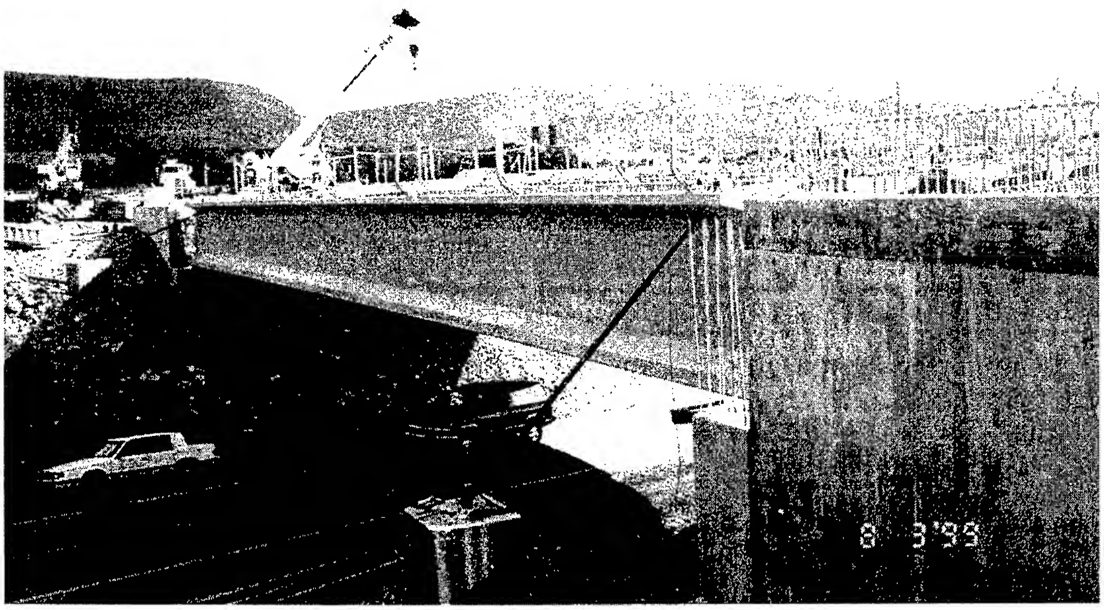

Figure 2.4 Weaver Hill Bridge

Bridges 24 & 25

Bridges 24 & 25 are two similar bridges running side-by-side being constructed by contractor B. Both bridges consist of four spans covering a total length of 380 feet, 42 feet in width. The deck of the bridge consists of cast in place concrete supported by prefabricated, pre-stressed concrete I-beams. Cast in place concrete piers and abutments

support the I-beams. See Figure 2.5. The maximum working height above ground level is 59 feet. The estimated cost of the two structures is $2.882M.

Figure 2.5 Bridges 24 & 25

Bridges 28 & 29

Bridges 28 & 29 are also being constructed by Contractor B. These two bridges are single span bridges with lengths of 242 and 228 feet respectively. The concrete deck of each bridge has a width of 50 feet and is supported by composite steel girders. The girders are supported on each end by the abutment walls. The maximum working height is 35 feet above ground level. Total cost of these bridges is $5.603M.

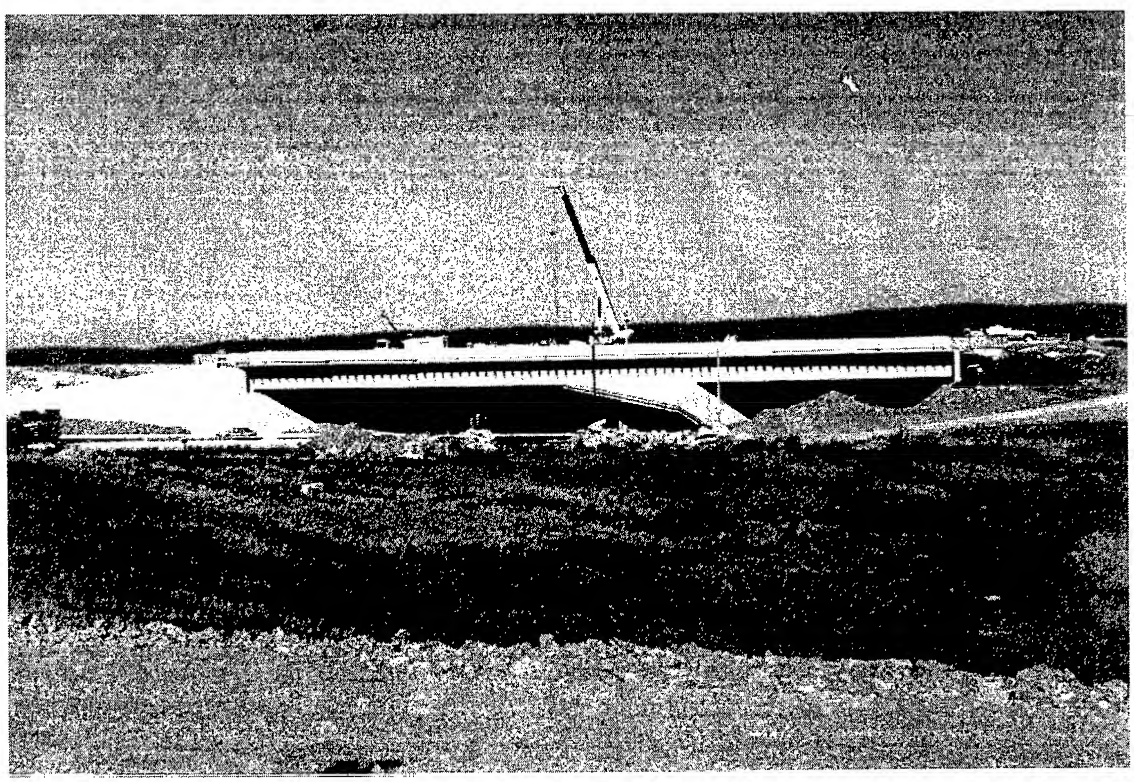

Figure 2.6 Bridges 28 & 29

Organization

The general organization of the four bridge projects was very similar. The prime contractor on each project provided a multi-skilled crew. These crews were responsible for formworks and concreting. These crews consisted of a mix of carpenters and laborers. Further, management typically supplemented crews with additional laborers on days concrete work was done. The second crew on each of these projects was the steel reinforcement crew. These crews consisted solely of ironworkers. On all four projects, a subcontractor provided these crews.

Crew sizes were different on each project. Logan Branch formwork crews typically consisted of the foreman plus nine workers. Weaver Hill formwork crews consisted of eight workers including the foreman. Bridges 24 & 25 had five workers, and Bridges 28 & 29 typically had nine workers including the foreman. The number of workers on each bridge fluctuated daily based upon the amount of work available. The median crew size has been used as the typical crew size. This information and other pertinent project data are summarized in Table 2.1.

Formwork Inventory

Two types of formwork were used on all four of these projects, wooden and steel forms. With the exception of the Weaver Hill Bridge, wooden formwork was used primarily for bulkheads and other minor work. The wooden formwork was not interchangeable with the steel panels. On the Weaver Hill Bridge, the wooden formwork was used for footings and bulkhead work. Abutment walls on the Weaver Hill Bridge

were formed using steel forms. The wooden forms were not interchangeable with the steel forms for the purpose of forming the abutment walls on Weaver Hill Bridge.

Logan Branch used modular, steel forms. There were two different types of forms, straight and curved. The curved sections were only used on the pier stems. The straight sections were primarily used on footings, walls, pier stems, and pier caps. However, not all of the straight forms could be used on the pier stems or caps due to size constraints. This resulted in two different inventories available for use based upon the component of the bridge. The total inventory of formwork available for walls and footings was 6,740 square feet. The total inventory of formwork available for pier caps and stems was 5,208 square feet. Wooden formwork was constructed and used for bulkheads and other minor work. This project had an ample supply of formwork and never ran out.

Weaver Hill used a mix of steel and wooden forms. Wooden formwork was used on footings and bulkheads. Steel forms were used on the abutment walls. The total inventory available for erection was 1,423 square feet. There were two days when this projected ran out of forms. On workday 4 and 14, the crew had to stop production work in order to go to other project sites to get additional formwork.

Bridges 24 and 25 used modular, steel forms. Wooden forms were also used for bulkhead work. Start to finish data on this project only included erection of pier caps, footings and walls. Only straight formwork was used on these portions of the construction. While pier caps were being built, the inventory of formwork available was 1,198 square feet. Once construction of the abutments began, an additional 328 square

feet of formwork was available. During this phase of construction, the total inventory available was 1,526 square feet. This project never ran out of formwork.

Bridges 28 and 29 used modular, steel forms. The steel forms were for both the abutment footings and walls. Wooden forms were constructed for bulkhead work. The total inventory available was 6,442 square feet. This project never out of formwork.

Table 2.1 Summary of Pertinent Project Data

Project / Item	Bridges 24 & 25	Bridges 28 & 29	Logan Branch Bridge	Weaver Hill Bridge
Span (feet)	380 / 380	242 / 228	920 / 920	140
Width (feet)	42	50	43	52
Height (feet)	59	35	107	24
Deck Support	Pre-stressed Concrete Beams	Composite Steel Girders	Composite Steel Girders	Pre-stressed Concrete Beams
Piers	Yes	No	Yes	No
Cost	$2.882 M	$5.603 M	$8.094 M	$815 K
Crew Size	5	9	10	8
Primary Type of Formwork	Steel	Steel	Steel	Steel and Wood mix
Formwork Qty Piers / Pier Caps	1,198 sfca	N/A	6,740 sfca	N/A
Formwork Qty Footing/Abutment	1,526 sfca	6,442 sfca	5,208 sfca	1,423 sfca

Lead-time – Inventory Relationship

Theoretically, there is an indirect relationship between lead-time and inventory. When there is no lead-time between erection of formwork and stripping, all of the formwork is in inventory and is available to be erected. To a worker on site, no lead-time means at the end of the work day all of the formwork that has been previously erected has been stripped. As the lead-time gets larger, formwork is being erected and left in place longer as work steadily progresses. Hence, the formwork available to be erected (inventory) declines as lead-times increases. This assumes there is a finite amount of formwork available for the project and work progresses daily. This relationship is linear when variability is taken out of daily workflows. Figure 2.7 graphically depicts the relationship between lead-time and inventory.

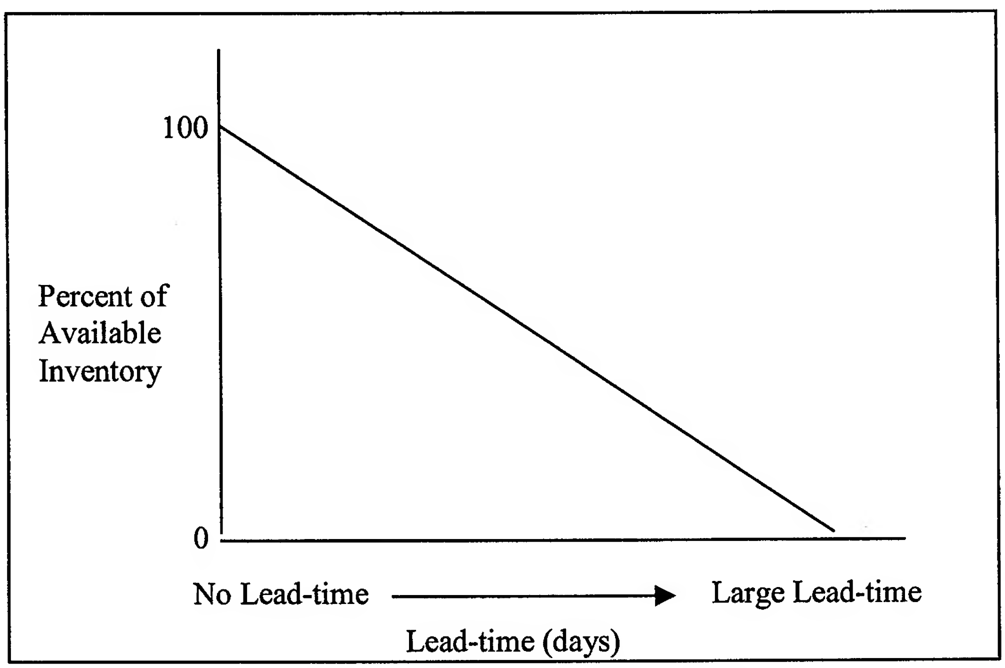

Figure 2.7 Inventory Lead-time Relationship

Data collected on the projects studied supports this relationship. A plot of the percentage of daily inventory of formwork available versus lead-time used on walls and footings in Figure 2.8 further demonstrates this concept. As can be seen, the size of the project has a large impact on the slope of this line. The larger projects tend to have greater amount of formwork on site as well as use larger lead-times to help deal with variability in the workflow. This suggests that the larger projects observed had poor formwork management. Larger projects maintain larger quantities of formwork and did not use the forms efficiently.

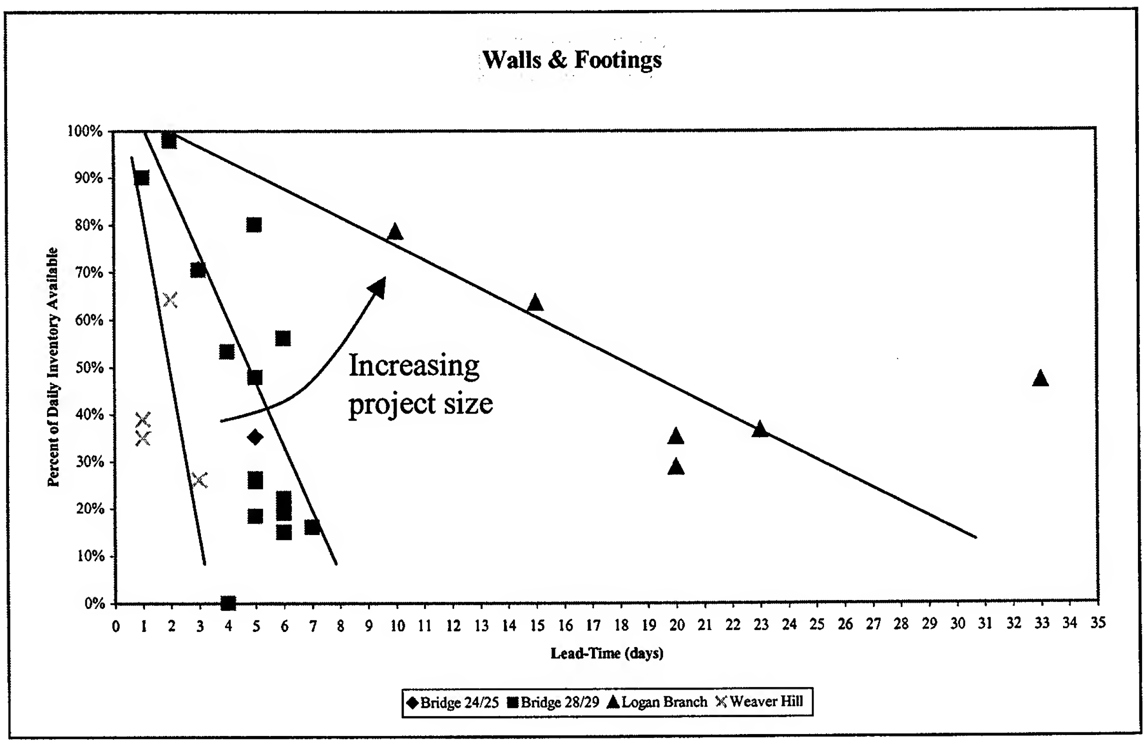

Figure 2.8 Walls & Footings Lead-time Inventory Relationship

CHAPTER 3

FACTORS AFFECTING PRODUCTIVITY

This chapter describes data processing and analysis. Performance parameters are calculated for each project and then are evaluated. The affect that management has on each of these projects is demonstrated. The chapter concludes with a discussion on crew sizing. An example of how managers can size a crew is given. Additionally, this method is used to evaluate and compare what was done on projects versus what should have been done.

Data Processing & Calculations of Performance Parameters

This section focuses on the processing of the data. Brief descriptions of project performance parameters are given. Further, this section describes how these project parameters are used to evaluate performance.

Rules of Credit

The first step in processing the raw data is determining rules of credit. Rules of credit are used to recognize partially completed work and provide an accurate completion status. (Thomas and Kramer, 1987) The rules of credit should reflect the relative

manpower effort required in completing a task. Formwork is divided into three categories: erection, plumbing, and stripping. Concrete placement has no major subtasks. Table 3.1 shows the rules of credit for formwork and concrete.

Table 3.1. Rules of Credit

Item	Errection/ Placement	Plumbing	Stripping
Formwork	0.75	0.15	0.10
Concrete	1.00		

Conversion Factors

To calculate daily productivity, various items must be converted into a standard item. The basis of conversion factors (CF) is earned value. (Thomas, Riley, and Sanvido, 1999). Table 3.2 depicts the conversion factors used in this thesis. The standard item in this thesis is wall formwork measured in square feet of contact area (sfca). Work that is more difficult to perform has a conversion factor greater than 1.0, while tasks easier than erecting formwork have a conversion less then 1.0. For example, erecting a square foot of footing formwork requires the same effort as only erecting 0.9 square feet of wall formwork.

Table 3.2. Conversion Factors

Item	Formwork (sfca)	Concrete (cy)
Walls	1.00	7
Footings	0.90	5
Pier Stems (round column)	0.85	10
Pier Cap (Beam)	0.90	7

Baseline Productivity

The baseline productivity is the best performance that a crew can do given the complexity of the work and no disruptions. The baseline productivity for each of these products is calculated in the following manner:

- The size of the baseline subset consists of 10% of the workdays, rounded up to the next odd number. No less then five days are used in any baseline subset.
- The days with the highest output are used for the baseline subset.
- The amount of work hours and output for each day are respectively summed.
- The baseline productivity is calculated by dividing the total workhours in the baseline subset divided by the total output in the baseline subset.

$$\text{Productivity} = \frac{\sum \text{workhours (wh)}}{\sum \text{output} \quad \text{(sfca)}}$$

As previously discussed, the baseline productivity represents the best performance a crew can achieve given the complexity of the work. Table 3.3 shows the baseline productivity for each project. Crews doing similar work should have similar baseline productivity results. However, it is unrealistic to simply compare projects based upon baseline productivity. The four projects studied are similar in the sense they are all bridge construction, but the work required on each bridge was different in size and design.

Table 3.3. Project Baseline Productivity

Project	Bridges 24 &25	Bridges 28 & 29	Logan Branch	Weaver Hill
Baseline Productivity	0.066	0.085	0.083	0.098

Cumulative Productivity

Cumulative productivity is a measure of both the job complexity and the work environment. Cumulative productivity is the total hours divided by the total output. This is the productivity that the crew actually achieved for a particular job. Ideally, the cumulative productivity should be very near to the baseline. Table 3.5 shows the cumulative productivity for each product. Each of theses projects took approximately twice as many man-hours than should have been required.

Table 3.4 Expected Productivity Determination

Project	Workday (from baseline subset)	Productivity	Component Worked Upon				Expected Productivity	Baseline Productivity
			Footing	Wall	Pier	Pier Cap		
Bridges 24 & 25	1	0.083				X	0.068	0.066
	2	0.078				X		
	6	0.056				X		
	13	0.043				X		
	20	0.089		X				
Bridges 28 & 29	8	0.058	X				0.094	0.085
	19	0.062	X					
	24	0.134	X					
	25	0.082	X	X				
	34	0.072		X				
	30	0.135		X				
	33	0.129		X				
Logan Branch Bridge	16	0.090			X		0.081	0.083
	19	0.052			X			
	29	0.109	X					
	35	0.076			X			
	40	0.087	X					
	44	0.094		X				
	54	0.108	X					
	68	0.065				X		
	75	0.073		X				
Weaver Hill Bridge	1	0.092		X			0.094	0.098
	2	0.081	X	X				
	5	0.130		X				
	9	0.080		X				
	10	0.123		X				
Average Component Productivity			0.090	0.098	0.073	0.065		
			0.094		0.068			

Expected Productivity

Expected productivity is the baseline productivity one should observe on the components that make up the baseline subset. The first step in determining the expected productivity for the case study projects is to calculate the average productivity for each component (footings, walls, pier stem, pier cap). This process is summarized in Table 3.4. The component productivity is calculated by averaging the daily productivities for each day the component is worked upon. For example, the component productivity for pier caps is the average of daily productivities from days pier caps were worked upon. These days, from Table 3.4, are from two projects (1) Bridges 24 & 25 workdays: 1, 2, 6, and 13 and (2) Logan Branch Bridge workday 68. The average of these daily productivities is the pier cap component productivity, 0.065 wh/sfca.

Due to the closeness of component productivities of piers and pier caps, these items are grouped together and assigned an average expected component productivity of 0.068 wh/sfca. Similarly, walls and footings are grouped together and the average component productivity is 0.094 wh/sfca. These values are used for subsequent calculations when determining the expected baseline productivity for a project.

The expected productivity for a project is the result of a weighted average of the component productivities contained with in that project's respective baseline subset. This is different from the baseline productivity because the baseline is the mean daily productivity of the subset. The expected productivity should be a number close to the

actual baseline productivity obtained. As seen in Table 3.4, they are nearly the expected productivities are nearly the same as the actual baseline productivity

Expected productivity is a developing theory that is still the subject of research. It provides a method for comparing components. Additionally, expected productivity calculations provide a basis for footings and walls being grouped together for analysis due to the relative closeness of the component productivities. Further, pier columns and pier caps can also be grouped together for analysis.

Project Management Index

To compare projects, the Project Management Index (PMI), also referred to as Project Waste Index (PWI), is calculated. The work environment influence on productivity is calculated by subtracting a project's baseline productivity from its cumulative productivity. Dividing it by the expected productivity then normalizes this number so different projects can be compared. PMI can be computed using the following equation:

$$\text{PMI} = \frac{\text{Cumulative Productivity} - \text{Baseline Productivity}}{\text{Expected Productivity}}$$

The PMI reflects how well a project was managed. It is a measure of how well management controlled the factors that influence productivity. An average job has a PMI equal to 0.5. Jobs better than average have a PMI less than 0.5.

Table 3.5. Project Performance Indexes

Project	Bridges 24 &25	Bridges 28 & 29	Logan Branch Bridge	Weaver Hill Bridge
Baseline Productivity	0.066	0.085	0.083	0.098
Cum. Productivity	0.149	0.132	0.173	0.181
Expected Productivity	0.072	0.094	0.087	0.097
PMI	1.15	0.50	1.05	0.86

Evaluations of Baselines

The first step in evaluating the projects is to evaluate the baseline productivities. The case study projects demonstrate reasonable performance with regards to the baseline productivity. The baseline productivities are similar, as they should be given that each project studied deals with highway bridge construction. Furthermore, they are similar to other highway bridge construction baseline productivities studied at The Pennsylvania State University. The closeness of the expected productivity compared to the actual baseline productivity, as seen in Table 3.5, provides additional support to the validity of the project baselines. Given that the baseline productivities of these projects are reasonable, these data sets can be used for further analysis.

Based upon each projects' PMI, none of the projects studied were particularly good. At best, Bridges 28 & 29 with a PMI of 0.5 was an average project. The other

projects suffered significantly from disruptions and workforce management issues. They had PMI values equal to or greater than 0.85, which is an indication that the work environment was not effectively managed.

<u>Effect of Management</u>

Management of the factors that affect productivity is a major function in any project. Productivity does not change at random. Therefore, no evaluation of project and productivity is complete until a cause – effect analysis is performed. This section provides an explanation of events from each project journal. The purpose is to help identify what actually happened on site. However, Logan Branch and Bridges 24 & 25 are so disruptive that some days cannot be explained and can only be accounted for by the ripple effect. The ripple effect occurs when projects are severally disrupted. The frequency of disruptions inhibits workers' ability to maintain good productivity. (Thomas and Oloufa, 1995)

Bridges 24 & 25

Figure 3.1 depicts the daily productivity for Bridges 24 & 25. The daily productivity is highly variable. The cumulative productivity is 0.149 wh/sfca, which is more than twice the baseline productivity. This in conjunction with a PMI of 1.15; it is clear this project was very disrupted.

Table 3.6 shows the journal of events for this project. The events that transpired on this project can be classified into two categories: disruptions and workforce management. Disruptions are inadequate resources or flow of work. Disruptions on this project included out of sequence work, availability of equipment, and weather. Workforce management issues deal with crew assignments and size. The primary management issues were crew interference, insufficient work, and overstaffing.

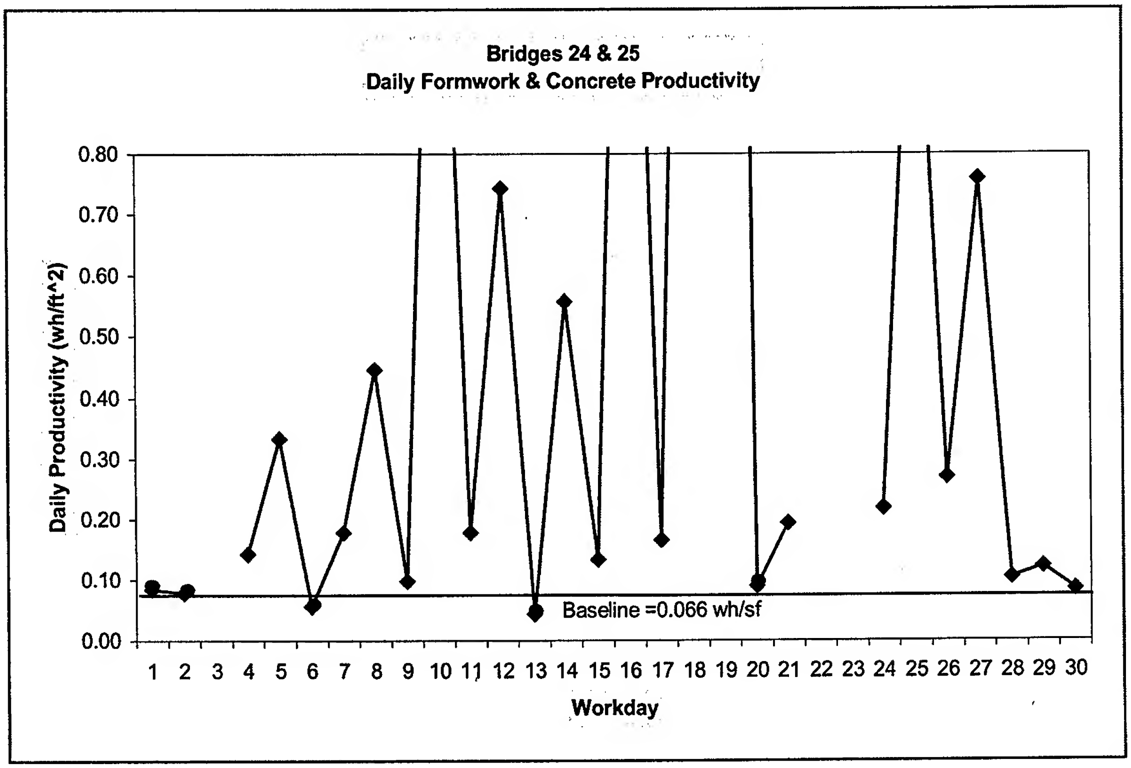

Figure 3.1 Daily Productivity, Bridges 24 & 25

Table 3.6. Bridge 24 & 25 Journal of Events

Workday	Quantity (sfca)	Workhours (wh)	Productivity (wh/sfca)	Remarks
7	336.9	60	0.178	Interference with steel crew erecting pier cap steel
8	112.3	50	0.445	Incidental work – site cleaning Lack of productive available
10	15.0	24	1.60	Removing thru bolts on pier cap - Insufficient productive work available
11	67.4	12	0.178	Strip ½ of Pier Cap formwork Insufficient productive work available
12	67.4	50	0.742	Strip ½ of Pier Cap formwork Insufficient productive work available
14	89.9	50	0.556	Interference with steel crew – no alternate work assigned – helped steel crew
16	15.0	28	1.87	Site Cleaning, Removing thru bolts – Insufficient productive work available
17	362.9	60	0.165	Positioned gabions Insufficient productive work available
18	25.2	60	2.381	Insufficient productive work available
19	11.5	60	5.240	Insufficient productive work available
21	361.2	70	0.194	Overstaffed for size of concrete pour
24	228.0	50	0.216	Rain
25	39.6	50	1.263	No crane available – used a backhoe instead
26	258.8	70	0.270	No crane available – used a backhoe instead Overstaffed for size of concrete pour
27	26.4	20	0.758	Rain, Site muddy

Crew Interference (Out of Sequence Work). This problem arose on workdays 7 and 14. On workday 7, the formwork crew had to wait while the steel reinforcement crew erected and positioned a rebar cage for the pier cap. The formwork crew was unable to plumb the formwork until the reinforcement crew was completed. No alternate

work was available. The formwork crew again waited on the steel reinforcing crew on workday 14.

Insufficient Work. On workdays 8, 10, 11, 14, 16, 17, 18, and 19, the formwork crews primarily did incidental work and accomplished little production work. This incidental work included site cleaning, placement of gabions, and removal of thru bolts. Incidental work, such as this, should be accomplished as part of normal production work.

Overstaffing. This primarily affected concrete placements. Table 3.7 shows the pertinent data on the days concrete was placed. Two additional crew members were added on workdays 4, 15, 21, and 26. Comparing these days to the days the additional workers were not present suggests that the additional workers were not needed. The productivity is better on both workdays 9 and 29. Furthermore, the effect of the additional workers on days when small placements are made only magnifies the problem.

Table 3.7. Bridge 24 & 25 Concrete Placements

Workday	Component	Concrete (cy)	Workhours (wh)	Productivity (wh/sfca)	Remarks
4	Pier Cap	70	70	0.143	
9	Pier Cap	70	48	0.098	
15	Pier Cap	70	77	0.133	Formwork also erected
21	Footing	30	70	0.194	Formwork also erected
26	Wall	30	70	0.270	Formwork also erected No crane, used backhoe
29	Wall	29	50	0.122	Formwork also erected

Bridges 28 & 29

Figure 3.2 shows the daily productivity for formwork and concrete for this project. The PMI is 0.50 indicating that this was an average project. The cumulative productivity was 0.132 wh/sfca versus the baseline productivity of 0.085 wh/sfca.

Table 3.8 shows the journal of events for this project. Much like Bridges 24 & 25, this project experienced both disruptions and workforce management problems. The disruptions experienced include out-of-sequence work, equipment availability, congestion, and weather. The congestion was due to restricted access, a product of the design, and not due to the contractor assigning too many craftsmen to the area.

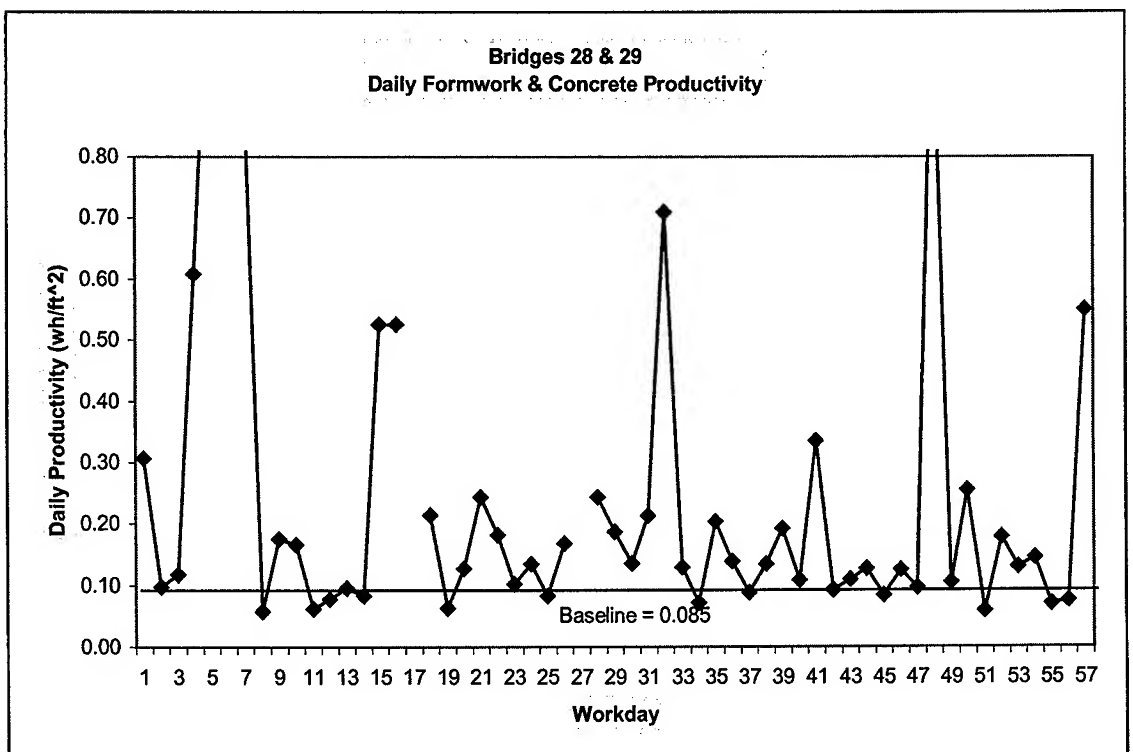

Figure 3.2 Daily Productivity, Bridges 28 & 29

Table 3.8. Bridges 28 & 29 Journal of Events

Workday	Quantity (sfca)	Workhours (wh)	Productivity (wh/sfca)	Remarks
1	208.9	64	0.306	Rain
2	277.6	27	0.097	Rain
4	131.7	80	0.608	Erect & Brace Formwork Insufficient work to perform
5	68.8	80	1.163	Only Braced Formwork Insufficient work to perform
6	34.4	32	0.930	Only Braced Formwork Insufficient work to perform
9	400.0	70	0.175	Subgrade elevation wrong – crew leveling to proper elevation
10	422.6	70	0.166	Subgrade elevation wrong – crew leveling to proper elevation
13	1251.9	120	0.096	Crane being shared with rebar crew
15	133.2	70	0.526	Only Braced Formwork Insufficient work to perform
16	133.2	70	0.526	Only Braced Formwork Insufficient work to perform
17	0	90	∞	Crane being shared with rebar crew Crew Performed Site Cleanup Insufficient work to perform
18	327.2	70	0.214	Crew doing piecemeal work Insufficient work to perform
21	493.6	120	0.243	Only Braced Formwork Insufficient work to perform
27	0.0	22.5	∞	Crew setting up for concrete pour Insufficient work to perform
28	987.8	240	0.243	Crew had to wait for concrete Insufficient work to perform
29	796.9	149	0.187	Rain
32	296.2	210	0.709	Restricted Access (design)
35	1228.6	250	0.203	Crew performed site cleanup Insufficient work to perform
38	594.0	80	0.135	Crew setting up for concrete pour Insufficient work to perform
41	389.1	130	0.334	Only stripped formwork Insufficient work to perform
48	120.0	130	1.083	Only Braced and setup for concrete pour – Insufficient work to perform
50	587.8	150	0.255	Rain
51	1358.0	80	0.059	Rain
52	559.5	100	0.179	Set up and placed concrete Insufficient work to perform
54	483.0	70	0.145	Rain
57	72.8	40	0.549	Rain

Insufficient Work. From an examination of Table 3.8, it is clear to see that this crew encountered problems with workflow. There are 15 days when the crew has insufficient work to perform. On six of these days, the crew only braced formwork that has already been erected. Other incidental work was also performed on these 15 days including site cleaning and setting up for concrete placements. Also important to note, is the fact that insufficient work is available on four consecutive days, 15 through 18. This suggest that the crew slowed its production rate to make the work that was available last longer. The lack of sufficient work has a tremendous negative impact on productivity. Table 3.8 shows that all these days are greater than twice the baseline productivity of 0.085 wh/sfca. Moreover, over half of the days are greater than six times the baseline productivity.

Overstaffing. An analysis of the days when concrete was placed was again conducted. Table 3.9 shows the data for these days. It is important to note that formwork was erected on all of the days concrete was placed. Half of the days when a placement occurred are significantly higher than the baseline productivity. The productivity on days 9, 10, 22, 28, 33, 36, 39, 46, 53, and 54 was over 45 percent worse than the baseline. On these days, either the crew placing concrete was overstaffed or the formwork assigned to the remainder of the crew was insufficient.

Table 3.9. Bridges 28 & 29 Concrete Placements

Workday	Component	Concrete (cy)	Workhours (wh)	Productivity (wh/sfca)	Remarks
8	Footing	570	165	0.058	Rain Formwork also erected
9	Footing	80	70	0.175	Subgrade needed to be leveled (grade elevation wrong) Formwork also erected
10	Footing	10	70	0.166	Subgrade needed to be leveled (grade elevation wrong) Formwork also erected
11	Footing	250	77	0.062	Formwork also erected
12	Footing	83	32	0.077	Formwork also erected
19	Footing	780	246	0.062	Formwork also erected
22	Abutment	95	120	0.181	Formwork also erected
23	Abutment	30	114	0.102	Formwork also erected
28	Footing	136	240	0.243	Formwork also erected
33	Footing	90	190	0.129	Formwork also erected
34	Footing	630	290	0.072	Formwork also erected
36	Footing	150	104	0.139	Formwork also erected
39	Abutment	90	180	0.192	Formwork also erected
40	Abutment	150	130	0.108	Formwork also erected
43	Abutment	70	140	0.109	Formwork also erected
45	Abutment	137	80	0.083	Formwork also erected
46	Abutment	80	70	0.125	Formwork also erected
49	Abutment	205	150	0.105	Formwork also erected
53	Abutment	115	130	0.130	Formwork also erected
54	Abutment	69	70	0.145	Rain Formwork also erected

Logan Branch Bridge

Figure 3.3 shows the daily productivity for Logan Branch Bridge. As can be seen, there is tremendous variability in the daily productivity on this project. The cumulative productivity is 0.173 wh/sfca versus the baseline of 0.083 wh/sfca. Further, the PMI on this project is 1.05 indicating this project performed poorly.

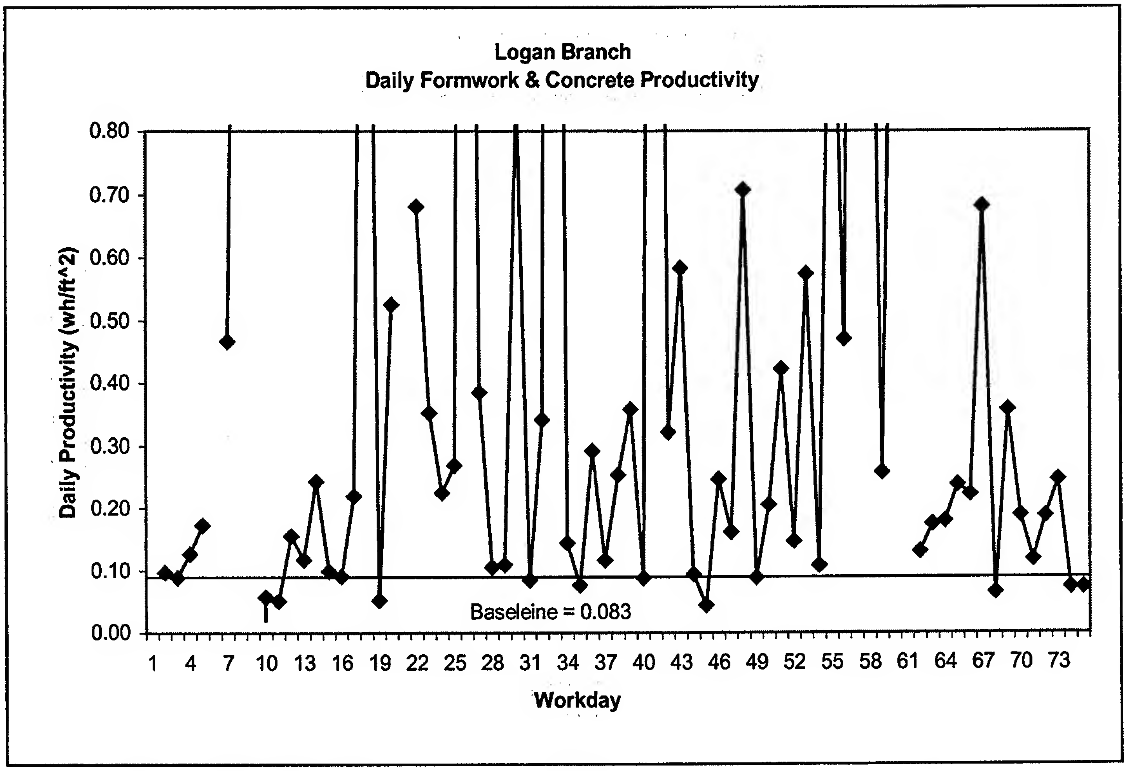

Figure 3.3 Daily Productivity, Logan Branch Bridge

Table 3.10 shows the journal of events for this project. This project also suffered from disruptions and workforce management issues. The disruptions include equipment availability / maintenance, weather, rework, and a design error. Of the disruptions, the most significant is the design error. On workday 17, it was discovered that the locations for two pier footings were incorrectly positioned on the plans. The concrete placement on one of these footings scheduled for the next day was canceled. This design error led to nine days of rework performed on workdays 20, 30, 32, 33, 39, 47, 51, 52, and 55.

<u>Equipment Availability</u>. Crane availability was also a significant disruption. On days 8 and 16, the crew shared the crane with the steel reinforcement crew. Furthermore,

the crane experienced maintenance problems twice on days 23 thru 27 and days 58 thru 59. On the days the crane was shared or broken down, only one day, workday 16, approaches the baseline productivity of 0.083 wh/sfca. The other days are at all greater than three times worse than the baseline productivity.

Insufficient Work to Perform. There are 11 days when the crew had insufficient work to perform. These days were primarily associated with days prior to a concrete placement. With nothing else to do, the crew stretched the workday with setting up for the placement. Other tasks that were carried out include bracing or stripping of formwork for most of the day, and site cleanup. These tasks should have been included in normal production work. As can be seen in table 10, the productivity on these 11 days was significantly worse than the baseline productivity.

Overstaffing. Table 3.11 shows data from the days when concrete was placed on the Logan Branch Bridge. There are three days when formwork was erected on the same day concrete was placed. In general, the crew appears to have been properly sized for most placements. However, the productivities on workdays 39, 50, and 65 are significantly worse than the baseline productivity of 0.083wh/sfca. Clearly, the rework on workday 39 significantly impacted the productivity. The crew on workday 50 appears to have been overstaffed given the small size of the placement. On workday 65, either the concrete placement was overstaffed or the formwork erected on this day was poorly planned or executed.

Table 3.10. Journal of Events, Logan Branch Bridge

Workday	Quantity (sfca)	Workhours (wh)	Productivity (wh/sfca)	Remarks
4	636.5	80	0.126	Rain
7	107.1	50	0.467	Setting up for concrete placement Insufficient work to perform
8	21.4	42	1.961	Shared crane operator, Set up for concrete, site cleaning – Insufficient work to perform
9	0.0	60	∞	Insufficient work to perform
14	452.9	110	0.243	Setting up for concrete placement Insufficient work to perform
17	583.2	121	0.207	Design Error in layout of piers 3 and 4 – results in later rework
18	110.2	220	1.997	Insufficient work to perform
20	209.4	110	0.525	Rework on Pier 3
22	146.9	100	0.681	Constructed work platform on pier formwork
23	284.6	100	0.351	Crane breakdown
24	312.1	70	0.234	Crane breakdown
25	260.1	70	0.269	Crane breakdown
26	28.9	90	3.112	Crane breakdown
27	260.1	100	0.384	Crane breakdown
30	116.64	100	0.857	Rework on Pier 3
32	382.3	130	0.340	Constructed work platform on pier formwork and Rework on Pier 3
33	30.24	110	3.638	Rework on Pier 3
36	343.4	100	0.291	Setting up for concrete placement Insufficient work to perform
39	280.5	100	0.357	Rework on Pier 3
41	38.3	120	3.130	Setting up for concrete placement Insufficient work to perform
42	311.0	100	0.322	Constructed work platform on pier formwork
43	257.5	150	0.582	Constructed work platform on pier formwork and Rain
47	620	100	0.161	Rework on Pier 3
48	128.7	91	0.707	Insufficient work to perform Crew bracing and stripping formwork
50	195.0	40	0.205	Rain
51	190.0	80	0.421	Rework on Pier 3, building work platform on pier

Table 3.10 Continued. Journal of Events, Logan Branch Bridge

Workday	Quantity (sfca)	Workhours (wh)	Productivity (wh/sfca)	Remarks
52	897.1	132	0.147	Rework on Pier 3
53	174.4	100	0.573	Setting up for concrete placement Insufficient work to perform
55	93.8	120	1.280	Constructed work platform on pier, ran out of thru bolts, patched concrete
56	127.7	60	0.470	Braced and Stripped formwork Insufficient work to perform
57	42.5	110	2.587	Constructed work platform on pier formwork
58	63.4	110	1.578	Constructed work platform on pier formwork
59	349.0	90	0.258	Crane breakdown
67	64.6	44	0.681	Only striped formwork – Insufficient work
69	252.5	90	0.357	Constructed work platform on pier formwork
70	292.5	72	0.246	Constructed work platform on pier formwork

Table 3.11. Logan Branch Bridge Concrete Placements

Workday	Component	Concrete (cy)	Workhours (wh)	Productivity (wh/sfca)	Remarks
10	Pier	75	42	0.056	
15	Pier	71	70	0.099	
19	Pier	291	150	0.052	
37	Footing	100	60	0.116	Formwork also erected
39	Footing	56	100	0.357	Rework on Pier 3
40	Footing	461	200	0.087	
50	Footing	39	40	0.205	Rain
54	Footing	667	360	0.108	
62	Pier Cap	110	100	0.130	Formwork also erected
65	Abutment	37	90	0.237	Formwork also erected
71	Pier	68	80	0.118	
74	Pier Cap	110	56	0.073	

Weaver Hill Bridge

Figure 3.4 shows the daily productivity for Weaver Hill Bridge. There is considerable variation in the daily productivity. From Table 3.5, the PMI for this project was 0.86 indicating that this project performed poorly. Further, the cumulative productivity of 0.181 wh/sfca was significantly higher than the baseline productivity of 0.098 wh/sfca. This also indicates that this was a subpar project.

Table 3.12 shows the journal of events for this project. The primary problems on this project were disruptions. These included out-of-sequence work, material shortages, and adverse weather.

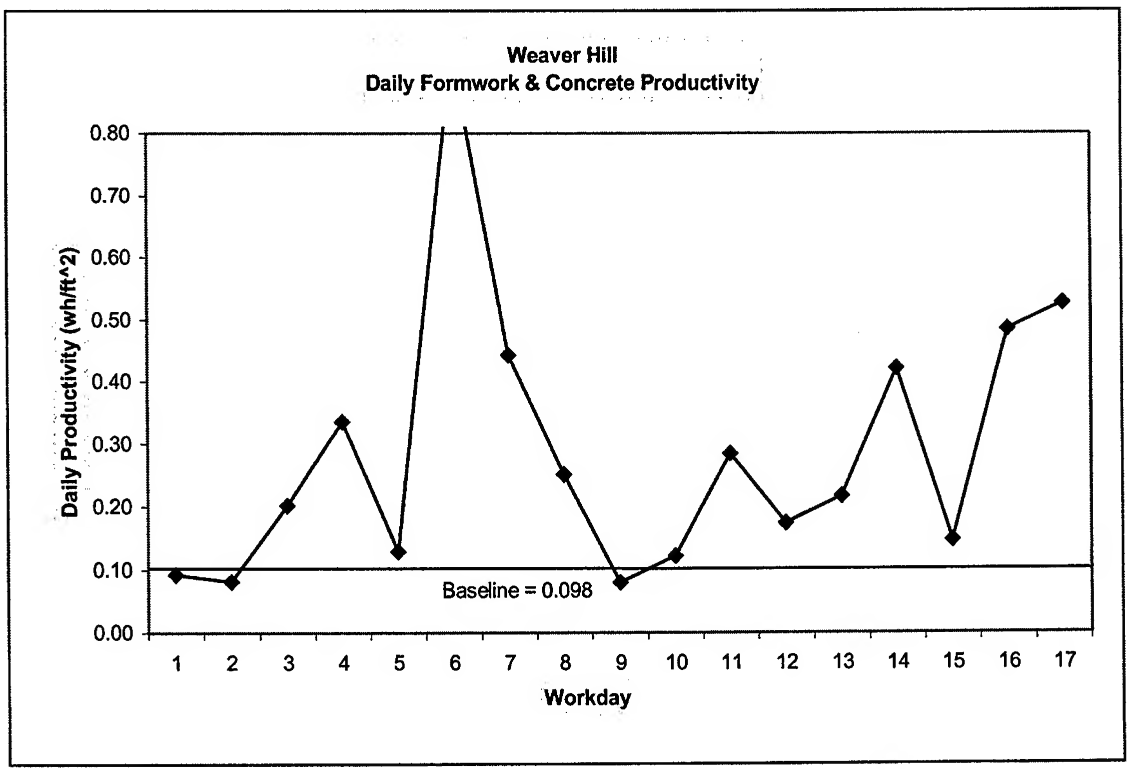

Figure 3.4 Daily Productivity, Weaver Hill Bridge

Table 3.12. Journal of Events, Weaver Hill Bridge

Workday	Quantity (sfca)	Workhours (wh)	Productivity (wh/sfca)	Remarks
3	346.4	70	0.202	Crew had to level subgrade (elevation was wrong)
4	74.5	25	0.335	Insufficient formwork; Rain
6	129.1	120	0.930	Rain
8	398.4	100	0.251	Crew had to drill and install dowels in the top of the abutment wall
11	316.5	90	0.284	Concrete delivery did not arrive
13	552.6	120	0.217	Insufficient work to perform
14	246.6	104	0.422	Insufficient formwork
16	41.2	20	0.485	Hauling forms to another site, crew waits for truck to return
17	94.8	50	0.527	Hauling forms to another site, crew waits for truck to return

Material Shortage. Most significant disruption was material shortages. There were two days, workdays 4 and 14, when the crew ran out of formwork. The crew was forced to retrieve formwork from other sites to continue work. The productivity on both of these days was very poor.

Overstaffing. Table 3.13 shows data from the days when concrete was placed on Weaver Hill Bridge. Except for workday 12, formwork was erected on each day that concrete was placed. There are three days when the productivity was very poor, workdays 7, 12, and 15. Workday 12 appears to have been overstaffed for the size of the concrete placement. On workdays 7 and 15, either the crew doing the concrete placement was overstaffed or the formwork assigned to the remainder of the crew was insufficient.

Table 3.13. Weaver Hill Bridge Concrete Placements

Workday	Component	Concrete (cy)	Workhours (wh)	Productivity (wh/sfca)	Remarks
1	Abutment	24	86	0.092	Formwork also erected
2	Footing	26	78	0.081	Formwork also erected
7	Abutment	47	120	0.443	Formwork also erected
9	Abutment	69	80	0.080	Formwork also erected
12	Abutment	58	70	0.174	
15	Abutment	73	80	0.147	Formwork also erected

Use of Baseline Data

Overstaffing can have a devastating impact on productivity. As seen in the previous journals, crew staffing and work assignments based upon the work available is a critical management task. This appears to be a particular problem with concrete placements based upon trends in the data.

Managers can use baseline productivity data to assist in planning crew sizes and task duration. First, managers must determine the baseline productivity for the project. The manager must also plan the total workhours available. The total workhours available is calculated using the following equation:

$$\text{Total Workhours Available} = \text{Crew Size} \times \text{Hours Worked per Day}$$

Next the quantity of work to be completed is identified. It is also important to identify the location or component of the work. This allows conversion factors to be

applied in order to put the work in terms of the standard item. Once the work is in terms of the standard item, the workhours required for this task are determined.

$$\text{Required Workhours} = \sum_{i=1}^{n} CF_i \, Qty_i \times \text{Baseline Productivity}$$

The manager must next determine the time the task will take based upon environmental conditions. An example of environmental conditions may include material delivery schedule or availability of equipment. From this information, the manager can determine the productive crew size for this task by this equation:

$$\text{Productive Crew Size} = \text{Required Workhours} / \text{Time Required}$$

The manager can now develop crew expectations. Excess members of the crew should be assigned to other production work. First, one must determine the excess workhours available. Once this is done, the next step is to identify the type and location of the production work to be done. Now a manager can calculate the quantity of work the excess workers should be able to complete.

The excess workhours are equal to the total workhours available minus the required workhours for the task.

$$\text{Excess Workhours} = \text{Total Workhours Available} - \text{Required Workhours}$$

The excess workhours are then divided by the baseline productivity to achieve quantity of the standard item that the excess members of the crew can do.

Qty. of Standard Item = Excess Workhours / Baseline Productivity

The standard item is then divided by the conversion factor and rule of credit of the desired work.

Expected Qty = Qty of Standard Item / (Conversion Factor)(Rule of Credit)

The final product of this analysis should be a crew size and time required to complete the main task and expectations for excess members of the crew. Should the task not be done within the allotted time, the majority of the crew should be moved to other production work while a skeleton crew remains behind to complete the task. This procedure is graphically depicted in flow chart form in Figure 3.5.

Figure 3.5 by no means is a solution that will fit every situation. Figure 3.5 is simply meant to help the reader understand the overall process a manager must undergo. There are several ways this diagram could be varied, and should not be taken as a lock step solution method. However, this technique can be adapted effectively to help manage crews. Use of the baseline data, can help managers plan crew staffing and work expectations with regards to quantities and times required.

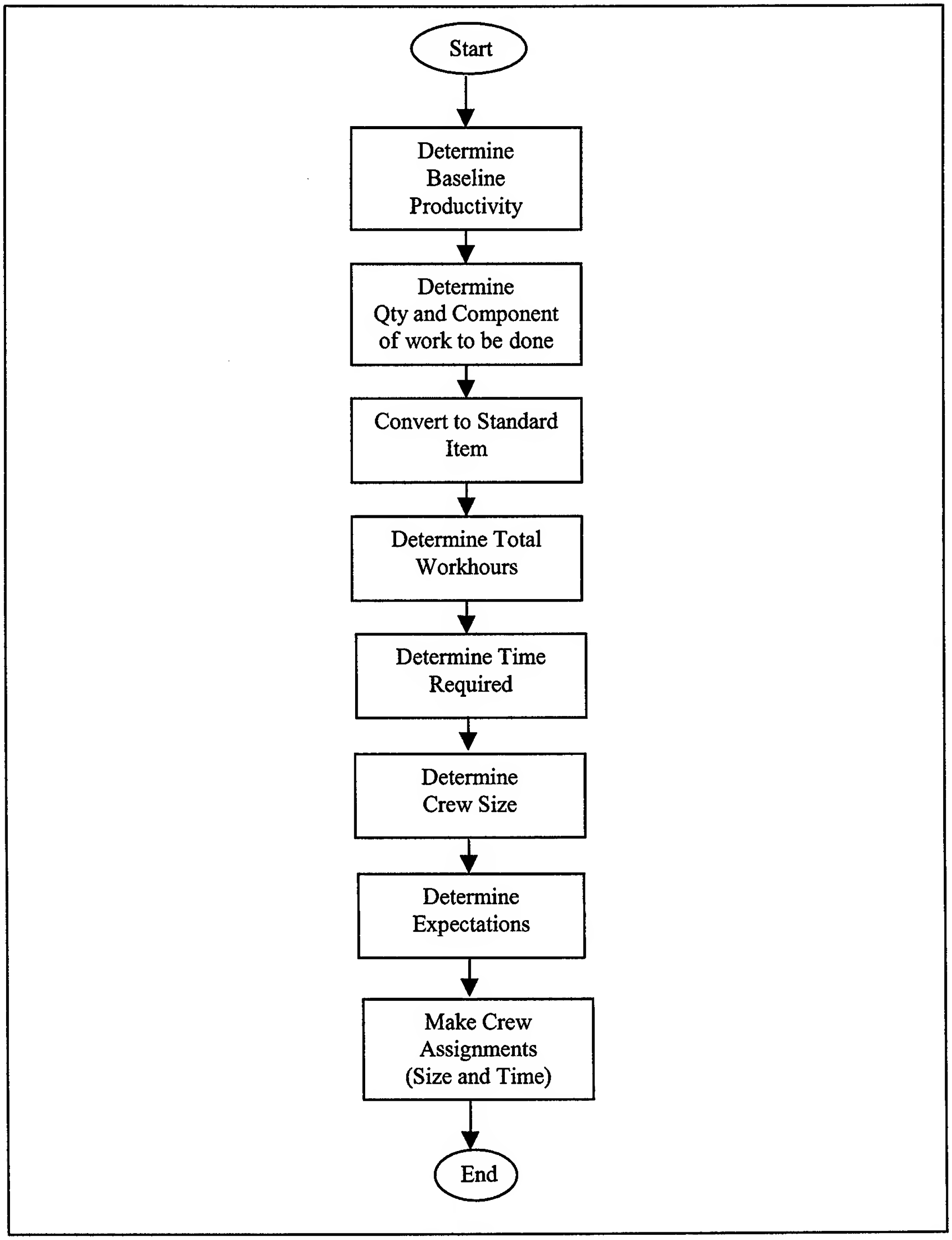

Figure 3.5. Crew Sizing Technique

Example

Suppose a manager wants to plan a 40 cubic yard concrete placement on an abutment wall. The manager needs to size the crew and determine the time to allot the crew to complete this task. Further, he must determine if the crew is capable of doing other work on this day. The typical crew size on this project is 10 workers, and the crew works 10 hours per day. The baseline productivity for this project is 0.080 wh/sfca. Based upon experience, the manager figures it will take four hours to complete the concrete placement. The standard item is wall formwork (square feet of contact area).

The first step the manager must do is identify the information that is readily available to him. This includes knowledge of the baseline productivity, 0.080 wh/sfca, and total workhours available in the day, 100 hours. Next, he must apply a conversion factor to put the placement in terms of wall formwork. From Table 3.2, the conversion factor for cubic yards of concrete placed in a wall section to the standard item is 7. Therefore, the equivalent quantity of wall formwork is calculated to be 280 sfca (40 x 7).

The manager can now calculate the time and quantity of workers the concrete placement will require. The workhours to complete this task are then calculated using the baseline productivity. The total workhours required to complete the concrete placement is 22.4 workhours (280 sfca x 0.080 wh/sfca) or 23 workhours. The manager can now staff the concrete placement with personnel by dividing the total workhours required by the estimated task duration. Since the placement is expected to take four hours, six personnel should be assigned to this task (23 wh / 4 hours).

The manager must now assign work for the other four members of the crew. Furthermore, he must have work available for the concreting crew upon completion of that task. The manager first determines that there are 76 hours still unplanned (100 wh – 24 wh). Knowing this, he can calculate the quantity of work, in terms of the standard item, that can be completed. This is calculated to be 950 sfca of wall formwork (76 wh x 0.080 wh/sfca). Suppose the other work available is erection of abutment wall formwork. Using the rule of credit for erection from Table 3.1, the expected quantity of work is calculated to be 1,267 sfca (950 sfca / (1)(.75)).

The manager should assign six personnel for four hours to the concrete placement. Upon completion of the concrete placement, these six personnel should be assigned to erect wall formwork for the remainder of the day. The four personnel not needed on the concrete placement should be assigned to erection of wall formwork for the entire day. The total quantity of work completed at the end of the day should be 40 cubic yards of concrete placed and 1,267 sfca of formwork erected.

Case Study – Concrete Placement on Logan Branch Bridge

On workday 71, 68 cubic yards of concrete were placed on a pier section. A crew of ten personnel worked eight hours on this task, making the total work hours 80 hours. At this point in the project, the crew was working eight hours per day; this task took the entire day. From Table 3.2, the conversion factor for concrete pier to the standard item, wall formwork, is 10.0. The productivity on this day was 0.118 wh/sfca, while the

baseline productivity, from Table 3.1, was 0.083 for the project. Other work available included erection of formwork on a footing.

This placement was clearly over staffed causing the productivity to be much worse than what it should have been. Using the crew sizing technique described, an analysis was conducted to see what should have happened versus what did happen.

First, the concrete placement on the pier stem was converted into wall formwork. A conversion factor of 10, from Table 3.2, was applied resulting in the quantity of work equal to 680 sfca of wall formwork (68 cy x 10). Next, the total workhours required to do this task was determined. Using the baseline productivity of 0.083 wh/sfca, the workhours required for this concrete placement was 56.4 workhours. It was assumed that this task required 8 hours to complete. The productive crew size for this task was then calculated by dividing the required workhours, 56.4 workhours, by the time required to complete this task, 8 hours. Based upon this calculation, the crew should have been staffed with seven workers for eight hours.

The analysis showed that there were three extra workers assigned to this task. These workers should have been assigned to erection of formwork on the footing. These three workers accounted for an excess 24 workhours. These three workers could have completed 289 sfca of wall formwork. This quantity was then divided by the conversion factor of 0.9, from Table 3.2, and the rule of credit for erection of 0.75, from Table 3.1, to determine the total quantity of footing formwork that could have been erected. These three workers could have erected 428 sfca of formwork on the footing.

In summary, only seven versus ten workers should have been assigned to the concrete placement for the duration of the day. The additional three workers should have been assigned to erection of formwork on a footing for the duration of the day. These three workers should have been able to erect 428 sfca in this time.

As can be seen, twenty-four workhours were inefficiently used on this day (three excess workers for eight hours). Three workers should have been assigned to the erection of formwork. Ultimately, inefficient workhours cut profits on projects. If each of these workers earns $20 an hour, the potential savings on this day would have been $480.

The use of base line data is a simple and effective way for managers to staff crews and develop work expectations for tasks. The end result is improved workforce management and more consistent productivity. Further, using this workforce management technique can lead to significant labor cost savings.

Summary

This chapter has described data processing and analysis. It further demonstrated how performance parameters are calculated and evaluated for projects. The chapter continued by showing the affect management has on projects through the use of the case study projects. The case study projects showed the devastating impact that disruptions and poor workforce management practices can have on productivity. Insufficient work and overstaffing proved to be a particularly troublesome problem. The chapter concluded with the development of a technique that managers could use to improve workforce

management. The case study demonstrated that by using this technique managers could better develop work expectations.

CHAPTER 4

LEAD-TIME – INVENTORY – PRODUCTIVITY RELATIONSHIPS

This chapter discusses the various relationships between lead-times, inventory, and productivity. The chapter begins with a discussion of how the data were processed with regards to project progression. The lead-time–productivity and inventory–productivity relationships are than examined. Next, the three-way relationship between lead-times, inventory, and productivity is demonstrated. The chapter concludes with a conceptual discussion of how to size lead-times, crew size, and inventories.

Calculations of Lead-times and Inventory

Lead-times and inventories are calculated from project progression charts. In these charts, the total percent of work completed versus workdays are plotted. Progression curves range from 0 to 100 percent complete.

In sequenced work, such as erection of formwork, concrete placement, and stripping of formwork, the curves of each respective work component should not intersect. If these craft progressions curves cross, it is an indication of out-of-sequence work. The lead-time, the horizontal distance, between the curves should ideally remain constant. This would reflect that each trade or component of the construction is progressing at the same rate daily. However, as can be seen in Figures 4.1 through 4.4, the work on these jobs did not progress in this manner.

The inventory of formwork available for erection, x_i, is calculated by subtracting the quantity of formwork in use from the total quantity of formwork on site. The total quantity of formwork in use is the vertical distance between the progression curves. It follows that if the lead-time between the formwork erection and stripping progression curves increases, the quantity of formwork available for erection decreases. This relationship was discussed in Chapter 2 and is depicted in Figure 2.7.

Figures 4.1, 4.2, 4.3, and 4.4 show the progression curves for each project. As can be seen, the lead-time between formwork erection and stripping change throughout the life of each project. The tendency on these projects was to erect formwork on a daily basis while allowing the quantity in use to increase. This was particularly true on pier columns. Formwork on pier columns was often left in place in order to support subsequent formwork higher on the columns. Stripping tended to happen sporadically. This is especially true of the Logan Branch Bridge.

From Figures 4.1 thru 4.4, one can see that current construction practices do not result in the production of identical quantities each day. There are many reasons for this. One reason is that identical items are not constructed every day. The items being constructed differed in size and shape. Larger concrete placements tended to require a greater amount of formwork and longer curing times. This alone does not allow for a constant output.

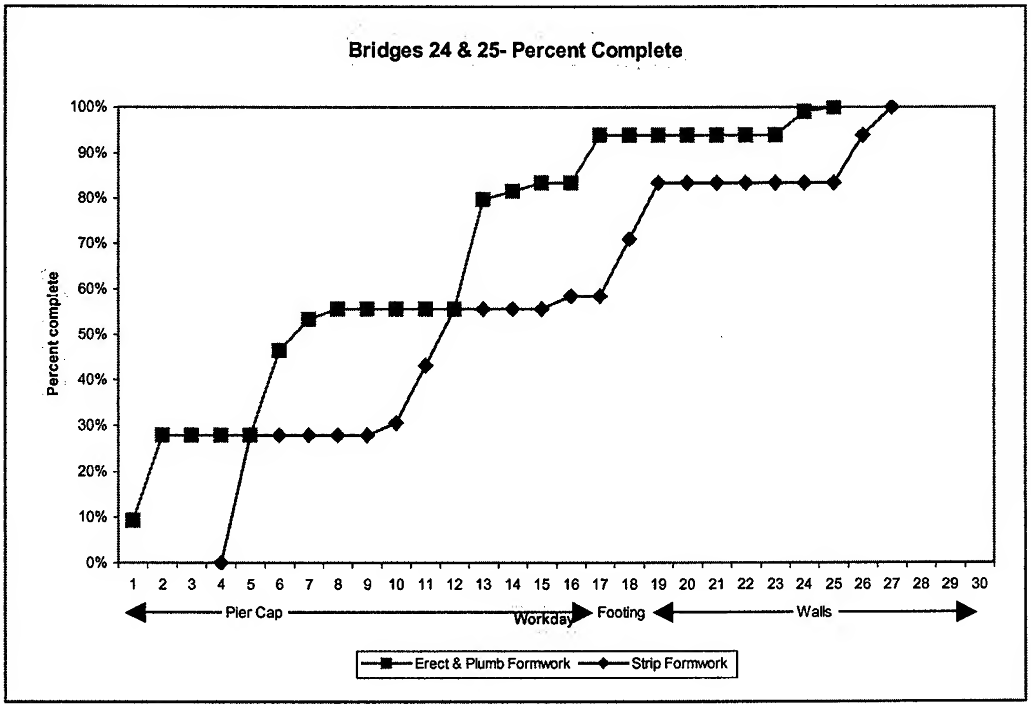

Figure 4.1 Bridges 24 & 25 Progression Curve, All Formwork

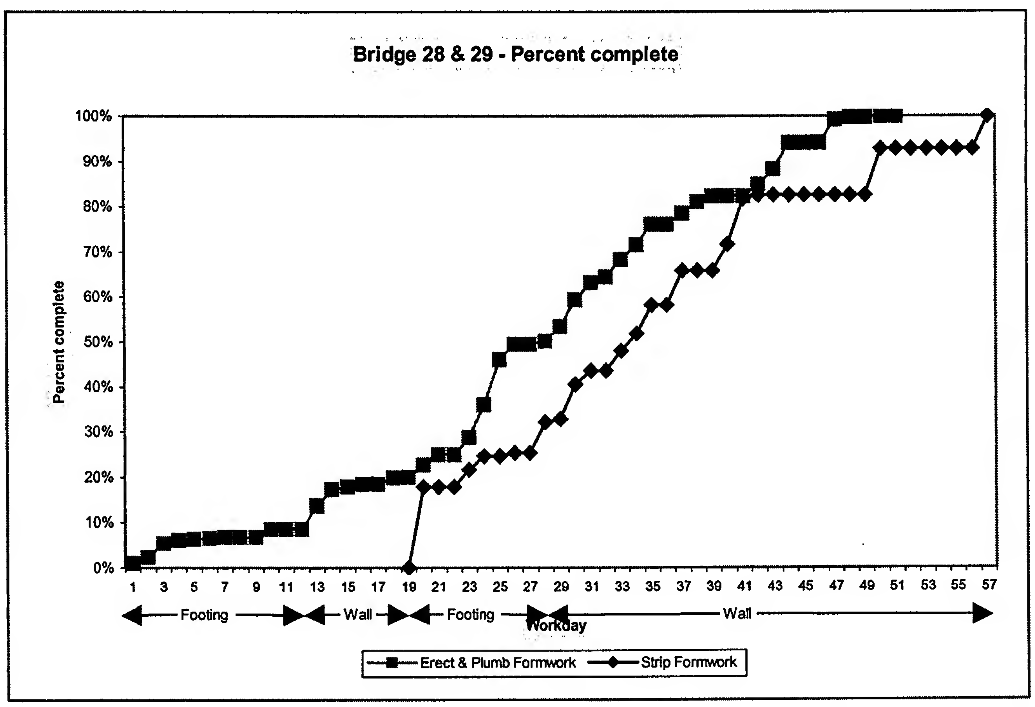

Figure 4.2 Bridges 28 & 29 Progression Curve, All Formwork

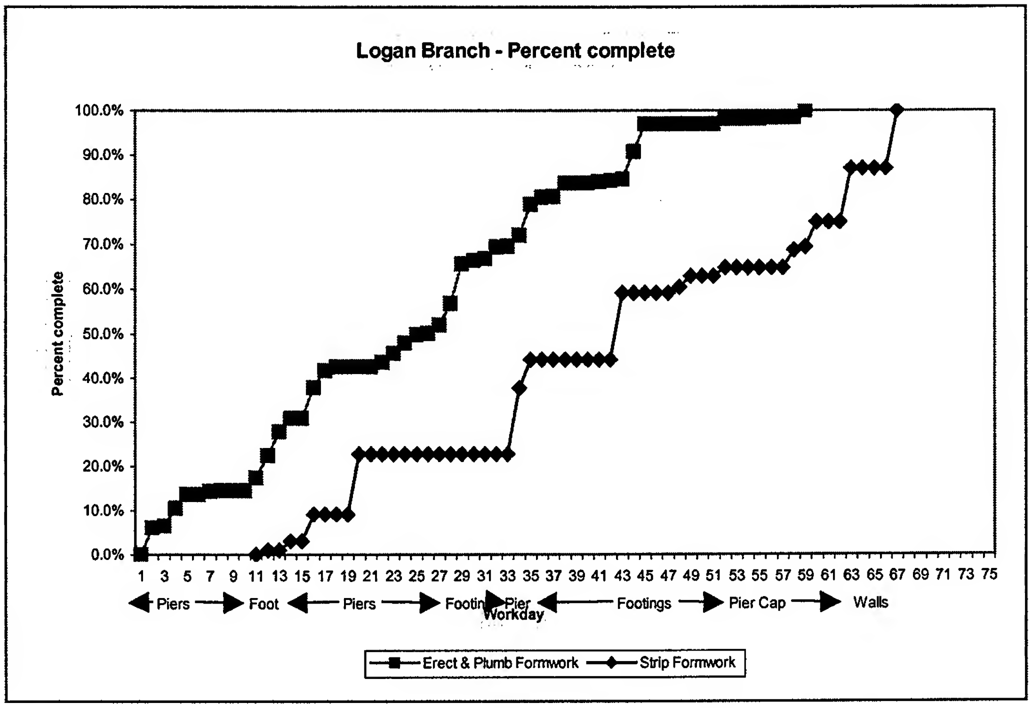

Figure 4.3 Logan Branch Bridge Progression Curve, All Formwork

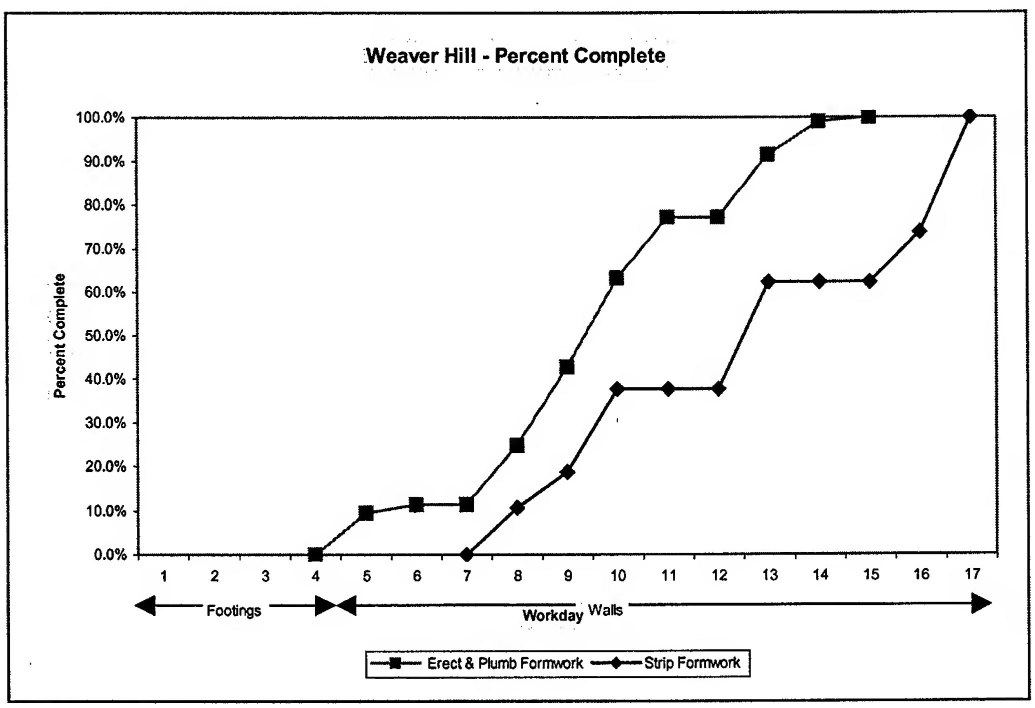

Figure 4.4 Weaver Hill Bridge Progression Curve, All Formwork

Data Limitations

The analysis in this chapter was limited to walls and footings. Upon inspection of the lead-time-inventory data, there were only three days when good productivity performance was achieved on days piers and pier cap work was conducted. Further, pier cap work was limited to one set of forms due to the size and character of work. Thus, it is omitted from any further analysis.

Two-Way Relationships

The first step in analyzing the data was to determine if there was any direct inventory-productivity or lead-time-productivity relationship. Figure 4.5 shows a scatter plot of daily productivity versus percent of daily inventory available. As can be seen, there is no apparent relationship. Figure 4.6 shows a plot of daily productivity versus lead-times. Again, there was no correlation between lead-time and productivity.

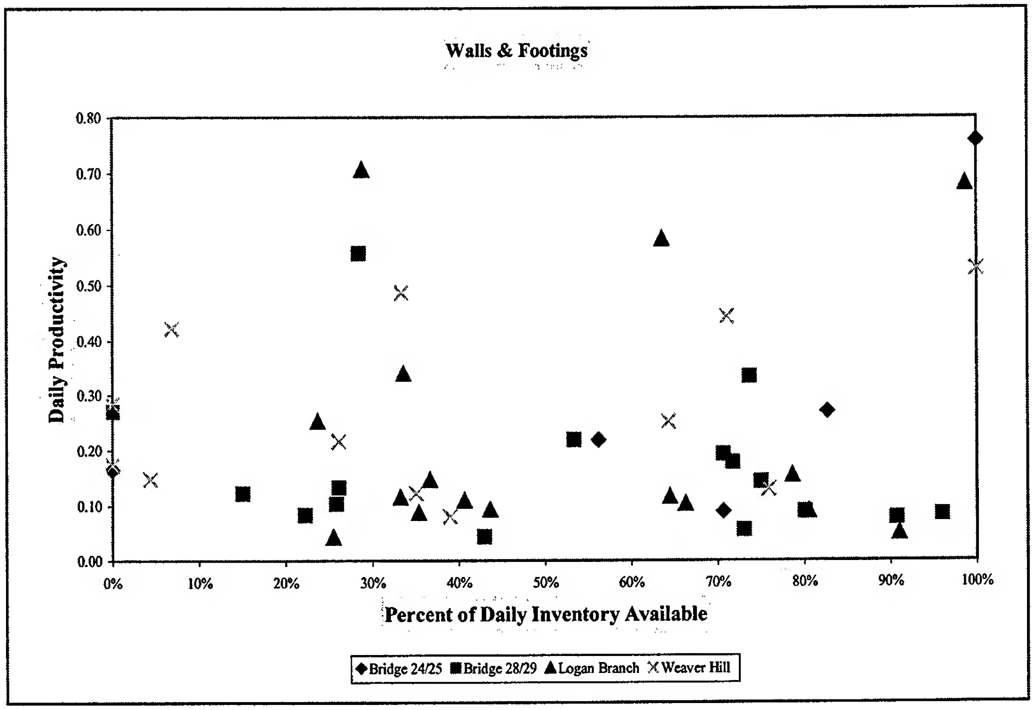

Figure 4.5 Productivity versus Inventory Available

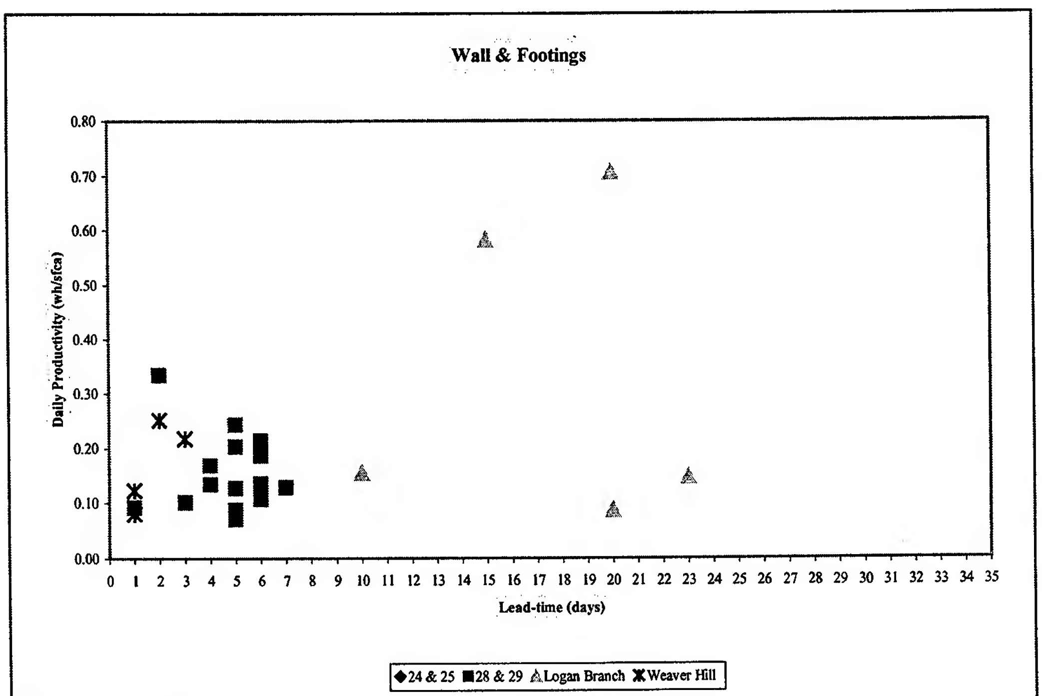

Figure 4.6 Productivity versus Lead-time

The Three Way Relationship

There is a relationship between lead-time and inventory available, as was shown in Chapter 2. As lead-times increase the quantity of formwork available for erection decreases. Figure 4.7 shows the daily productivity factors for each point on the lead-time-percent inventory plot. There are twelve days on this plot that demonstrated good productivity using 0.135 wh/sfca as the upper limit of good productivity. While neither lead-time nor inventory has a direct affect on productivity, it would appear that these two factors combined do have an influence on daily productivity. The relationship is not particularly strong with these data sets because the projects were so disrupted. The pattern of the data is linear with an extremely steep slope. When days with good daily productivity are regressed, the equation for the relationship in Figure 4.7 is:

$$\text{Percent Inventory Available} = [1 - 0.131(\text{Lead-time} - 1)] \times 100\%$$

This line passes through the point of (1, 100%) because a lead-time of zero would indicate that formwork is erected and stripped on the same day. During the regression analysis three points were removed as outliers. Logan Branch (lead-time 20, inventory 35%, productivity 0.09) was removed because the design error on this project resulted in the lead-time being exceptionally large. The two good productivity days on Weaver Hill were also removed as statistical outliers. The T statistic was –8.60, and the F statistic was 73.89. The relationship ranges from 1 day lead-time with 100% inventory to 0 inventory and a 8.6 day lead-time. Logically, one shouldn't work at either extreme. The data are distributed equally about the midpoint of this line. The mid-point of this line

occurs at a lead-time of 4.8 days. Further analysis was done to determine what the best quantity of inventory available was required to optimize daily productivity. The six days with the best productivity were selected from Figure 4.7. Half of these days fell within a range between 39 percent and 56 percent. These days were approximately centered on 50 percent. Based upon this analysis, to achieve consistent, good productivity performance crews needed to have a lead-time of approximately four and a half days with 50 percent of the formwork available for erection.

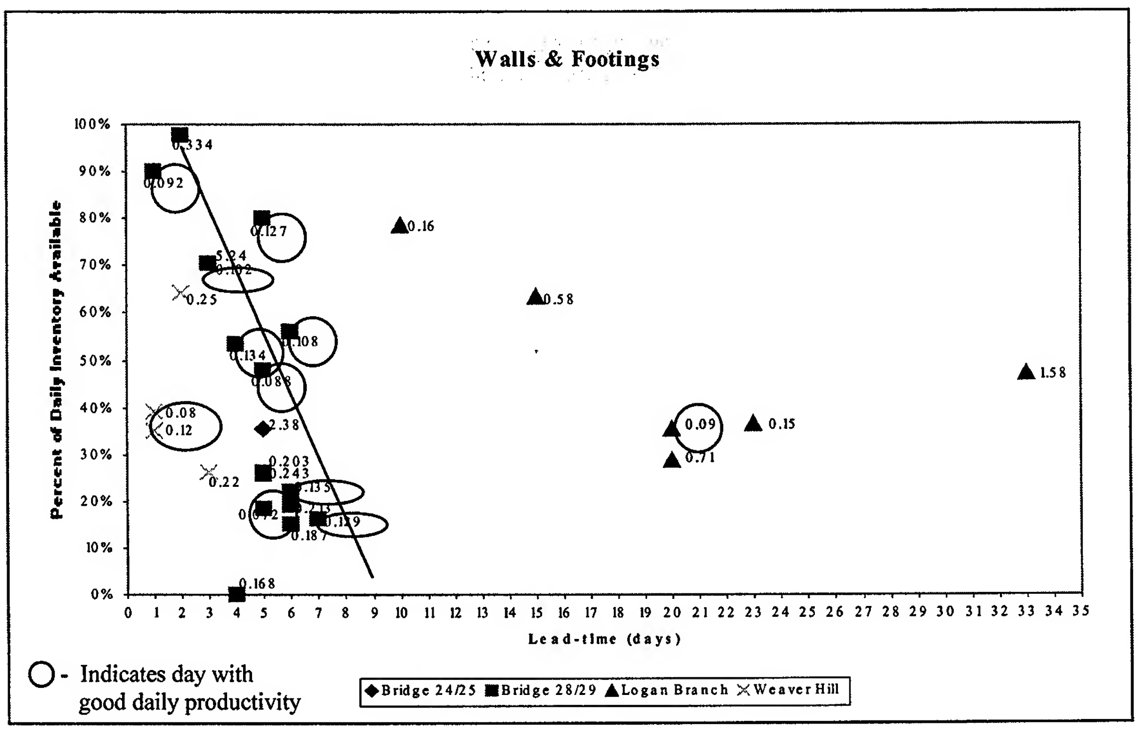

Figure 4.7 Inventory versus Lead-time with Productivity Results

The strength of this relationship is weak and requires further investigation for a number of reasons. First, each of these projects suffered from significant workforce management problems. Workforce management problems, such as over staffing, can have a serious negative impact on daily productivity regardless of the lead-time or inventory available. Furthermore, all four of the projects studied were essentially the same. Not only was the construction the same, but also the way the work was scheduled was very similar. Both contractors generally used a cycle time of four days between concrete placements. Because of these factors, the data sets are somewhat homogeneous.

Effect of Crew Size

Lead-times were normalized by the typical crew size for each respective project to obtain the lead-time per worker used. Figure 4.8 shows daily productivity values as the percent of inventory available versus lead-time per worker. When normalized, the inventory-lead-time relationship disappears. One can see, the good productivity days are centered on 0.5 days per worker. This means the lead-time should be about half as many days as the number of workers in the crew. For example, a crew with 10 workers should be using a lead-time of 5 days.

The size of a concrete placement is a function of the crew size and the cycle time or lead-time. Contractors on these projects were restricted in the size of concrete placements due to limits in the specifications, but they wanted to do the maximum placement as often as possible. If larger placements were allowed, either the cycle time or the crew size would have had to be increased. An increase in crew size or lead-time

requires the total inventory of formwork to also be increased. Say the crew size is increased, then the rate at which formwork is used increases. Therefore more formwork is needed. If the lead-time increases, formwork is erected and left in place longer. Again, more formwork is needed for work to progress.

Further analysis of the factors that potentially affected lead-times was conducted. The affect of the placement size and cycle time was examined. When the lead-time was normalized by these two factors, neither yielded any relationship.

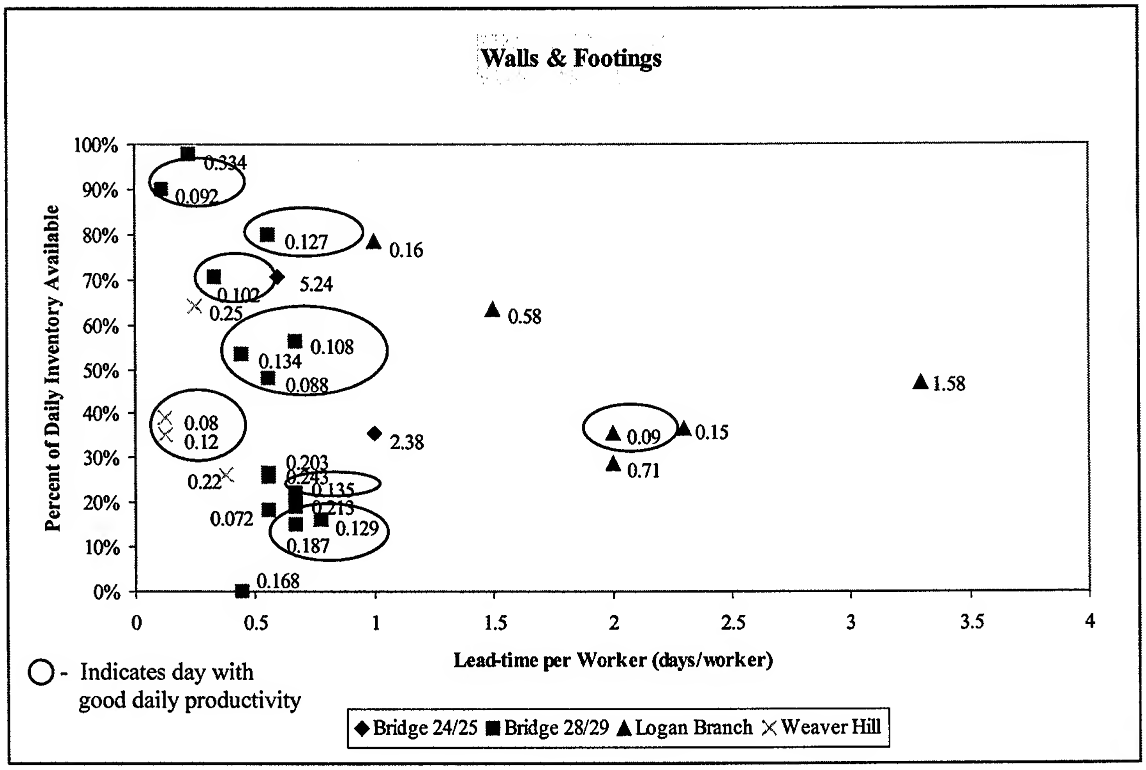

Figure 4.8 Inventory Available versus Lead-time per Worker with Productivity Results

Crew Size, Lead-time, and Inventory Interdependency

Base upon the previous analysis, there is an apparent interdependency between crew size, lead-time, and inventory. A change in any of these factors influences the other two. For example, if a crew size is reduced then the size of the lead-time is also reduced and the total quantity of formwork on site can be reduced. Furthermore, these three factors influence productivity. Crew size, lead-time, and inventory need to be balanced to consistently produce days with good productivity. Management should pay close attention to these three factors when planning a project.

Example

This concept is best illustrated through an example. Suppose a contractor is planning a bridge construction job. The work to be done consists of footings and abutment walls. Further, the contractor wants to have a cycle time of four days between concrete placements. The lead-time is equal to the cycle time. Knowing that for every day of lead-time there should be two workers, the manager then assigns eight personnel to the crew. Next, the manager must determine the total quantity of formwork that should be present for the project to achieve good productivity. The manager must first calculate the total number of work hours for each day. Say this crew will work eight hours a day, so the total number of daily workhours will be 64. The total number of workhours is then divided by the average component productivity, from Table 3.4, to determine the equivalent quantity of work planned to be produced daily. Since walls and footings are being constructed, the value of daily footing/abutment productivity is

determined to be 0.094 wh/sfca. Given 64 workhours and a daily productivity of 0.094 wh/sfca, the quantity of work produced daily should equal 681 sfca of formwork. This value now must be adjusted for the quantity needed for erection. Dividing by 0.75, the rule of credit for erection from Table 3.1, yields 908 square feet of formwork to be erected daily. However, to obtain good productivity the ratio of formwork available to be erected versus the total quantity of formwork must be 0.5. Therefore, the quantity of formwork is divided 0.5. From these calculations, the optimal quantity needed daily is 1,816 square feet of formwork. The final step the manager must take is to determine the total quantity the project will need. This is determined by multiplying the optimal quantity needed daily by the number of days in the cycle formwork will be erected. Assuming that concrete placement will account for half a day in the cycle, the daily quantity is multiplied by 3.5 days, which yields 6,356 square feet of formwork required for the project.

From this example, one can clearly see how a change in lead-time, crew size or inventory can affect the other two factors. Moreover, a change in anyone of these three factors without making the needed adjustments to the other two can lead to poor productivities through shortages of formwork or overstaffing.

Case Study – Logan Branch Bridge

This technique was tested on the Logan Branch Bridge project. This test was focused only on the wall and footing work done on Logan Branch Bridge.

An examination of Table 3.11 reveals that there was no one consistent cycle time between concrete placements. The cycle times between placements ranged from one to eighteen days. For the purposes of this case study, the median cycle time of four was selected as the planned duration.

Using a cycle time of four days as the lead-time, the remaining calculations of what theoretically should have happened were made. The crew should have been staffed with eight workers. This crew size is based on a half-day lead-time per worker. The crew on this project worked 10 hours per day meaning the total workhours available should have been 80 hours per day. The workhours were divided by both the average component productivity of 0.094 wh/sfca and the rule of credit for formwork erection, 0.75, to determine the daily quantity of formwork required which was 1,135 square feet. This number was divided by 0.5 to obtain the optimum daily inventory, 2,270 square feet. This value was multiplied by the number of days in the cycle formwork was erected, three, to obtain the total quantity that should have been on site, 6,810 square feet. Concrete placements on this project generally consumed an entire workday.

What actually happened on site was very different. First, the size of the lead-times was significantly larger. For walls and footings, lead-times ranged in size between 10 and 33 days. The average lead-time size was approximately 20 days. This was significantly different from the planned lead-time of 4 days. The crew size was also

different from the planning figures. The typical crew size on Logan Branch Bridge was 10 personnel. This was also larger then the theoretical value of eight workers. The quantity of formwork, however, was very close to what was calculated as the planning figure. The quantity of formwork available for walls and footings was actually 6,740 square feet. This is a mere 72 square feet less than the planning figure of 6, 810 square feet. Table 3.14 is a summary of theoretical values versus the actual.

Table 4.1. Logan Branch Bridge Crew Size, Lead-time, and Inventory Comparison

	Lead-time (days)	Crew Size	Inventory (sfca)
Theoretical	4	8	6,810
Actual	20	10	6,740

Inspection of Table 4.1 shows that crew size, lead-time, and inventory was not properly balanced. While the quantity of actual inventory appears to be properly sized based upon the theoretical lead-time, by no means was it in accordance with what actually happened. Both the lead-time and crew size were larger than what they should have been. The quantity of formwork should have been drastically increased based upon the increase in lead-time and crew size. The difference between the theoretical lead-time and the actual had the most dramatic impact. Clearly, formwork was erected and left in place for long periods of time making it unavailable for subsequent work. The overstaffing of the crew with two additional personnel simply magnified this problem. The overstaffing alone would create a need for an additional 2,128 square feet of

formwork. Given the size of the actual lead-times and the crew, there was a drastic shortage of formwork. An inspection of Table 3.11 supports this hypothesis. Table 3.11 shows there are 11 days when there was insufficient work to perform. The shortage of formwork ultimately resulted in the crew spending these 11 days doing large quantities of bracing, site clean up, and other incidental work normally incorporated in production work.

Summary

This chapter has examined the relationship between lead-times, inventory, crew size and productivity. Additionally, the use of craft progression curves to calculate lead-times and inventories was also explained. Using the calculated lead-time and inventories, the chapter demonstrated that no direct inventory-productivity or lead-time productivity correlation exist. Rather, lead-time and inventory tend to act with other factors to impact daily productivity. The chapter continued on by developing the optimal quantities of lead-times and inventory available. It further explained the interdependency of crew size, lead-times and inventories. It concluded with an example of how managers can use this interdependency as a planning tool and a case study to test this technique.

CHAPTER 5

SUMMARY AND CONCLUSION

Summary

The main objective of this thesis was to determine the relationship between lead-time, inventory, and daily productivity. In accomplishing the objectives of this thesis, a number of questions were answered. First, some of the significant factors that affected productivity were evaluated. Secondly, the relationship between lead-time and inventory was examined and then related to productivity. Additionally, two tools were developed to help managers determine workload expectations and plan lead-times, inventories, and crew sizes.

The factors that effected productivity on the case study projects were broken into two categories: disruptions and workforce management. Disruptions were classified as the inadequate follow of resources or work, while workforce management dealt with crew assignments and size issues. The primary disruptions encountered by the case study projects included out of sequence work, equipment availability, and material shortages. While these disruptions had a large negative impact on productivity, workforce management issues overshadowed these problems. Insufficient work to perform and overstaffing had a devastating effect on productivity. Insufficient work was apparent typically when crews performed a large amount of incidental work normally incorporated with production tasks.

This thesis shows a tool to help managers develop work expectations for crews. This simple process used baseline productivity, conversion factors, and rules of credit to help determine the work a crew should be able to perform in a day. Using this tool, managers can staff work with the appropriate amount of people for the appropriate amount of time. Furthermore, work expectations can be developed for other members of the crew not associated with each day's primary task. A case study demonstrating the use of this was presented.

A relationship exists between lead-times and inventory. As lead-times increase in size the quantity of formwork available for erection decreases. This is a very logical relationship. As formwork is erected and left in place longer, a larger lead-time, the quantity available to be erected decreases.

In meeting the ultimate objective of this thesis, the data showed that lead-times and inventory can be sized to improve productivity. There is an inherent relationship between lead-times, crew size and inventory. To increase the likelihood of good productivity performance, lead-times should be sized at half a day per worker and 50 percent of the inventory should be available to be erected.

This thesis demonstrates a tool to help managers balance lead-time, crew size, and inventory. This is primarily a planning tool. By first determining the lead-time size, by use of the cycle time, managers can then size the crew and determine the total quantity of formwork that a project needs. The case study demonstrates the effect on not balancing lead-time, crew size, and inventory.

Discussion of Findings

The results of this thesis run contrary to the principles of lean construction. This is especially true with regards to the quantity of inventory that needs to be available to produce good daily productivity. These results are partly a function of bad management. Management of the workforce and the work environment caused extensive problems.

Inventory

The data from the projects observed suggested you need twice as much formwork as what is actually going to be put up. Again, this finding appears to be more related to poor management then an inherent relationship to productivity. One of the reasons for the quantity of formwork required being so large is that crews on these projects had minimal confidence that these projects could maintain a regular schedule. In fact, concrete placement schedules on these projects were very erratic. As a result, the crews slowed down in order to maintain work available to them. Chapter 3 demonstrated how each of these four projects suffered tremendously from insufficient work to keep the crew busy.

Another factor contributing the observed projects achieving good productivity when 50 percent of the inventory was available is the formwork itself. The formwork came in a number of different sizes. All sizes were not

interchangeable, and there were times when certain sizes of forms were not required. As a result of this, these would sit idle as part of the inventory available. Additionally, the inventory included formwork that was damaged during the stripping procedure. This formwork was out of service until it was repaired and counted as part of the inventory.

Lead-time

The size of the required lead-time based upon the observed data is may also be skewed by a number of factors. These factors again are primarily management related. Among these factors are days when the workspace required was not available to the crew. This was experienced in the form of crew interference or out of sequence work. This problem was chiefly between the steel reinforcement crew and the formwork crew. There were days when work was ready to be completed, but the steel reinforcement crew was still erecting the rebar on wall sections. Additionally, the Logan Branch Bridge did not have the excavation for one of the pier footings done until well into the project. Had this been done earlier, this area would have been available for work to be done on days when there was insufficient work available.

Another factor effects the lead-time is the technique used to complete walls and footings. The way footings were constructed was that all the formwork would be erected and then the steel reinforcement bars would be placed with in the footing.

The footings on all the abutments and piers were large enough to accommodate this technique. However, wall sections require a different technique. Three sides of the formwork were first constructed. Next, the steel reinforcement crew erected the rebar and then the formwork crew would return to erect the forms on the fourth side of the wall section. The way the data was collected for this thesis, the lead-time between the first three side erected was not differentiated from when the fourth side was erected. The progression curves developed simply reflect the total percent complete at the end of any given workday. This potentially makes the observed lead-time greater then actual.

A final factor that affected the size of the lead-time is that it includes production time of stripping formwork. Lead-time should reflect the time between when the formwork was completed being erected until the beginning of the stripping process. However, the technique used to collect this data included the time that was used to actually strip the data. Data were collected at the end of each workday therefore the time required to strip the formwork was included in lead-time. Based upon the rules of credit for formwork, the inclusion of the production time potentially increases the observed lead-time results by ten percent. However, all data were collected consistently at the end of each workday. Therefore, the inclusion of production time in stripping of the forms should be somewhat offset by the fact that the formwork was not considered to be complete until the end of day when it was erected.

Results With Respect to Lean Construction

It would be rash to dismiss lean construction theory based upon the results of this thesis. On the contrary, the waste observed on these projects demonstrates the need to strive to improve construction practices. Based upon the observed projects, the solution does not simply lie in the strategic use of lead-time or inventory. The first step that needs to be taken is to improve management practices. Management of the workforce and the work environment tremendously impact the productivity on projects. Detailed planning must be incorporated into this management. The level of planning must include a plan on how formwork is going to be used on the project. For example, if just wall formwork was being conducted and a regular cycle time is kept, it is possible to plan the minimal quantity of formwork that is needed to meet production requirements. While one set of forms are in use, another set is being erected. Once the first set of forms is striped, they are immediately erected on another wall section, while concrete is being placed on the second set. Again, detailed planning must be done to get to this level.

Once management practices are fixed there will still exist a need for lead-time and inventory. Effective management can only reduce variability by eliminating assignable causes. Once this is done, lead-time and inventory can be brought down to an absolute minimum. However, there will always be some random variability that exist and justifies the use of lead-time and inventory.

Again, the first step in achieving this goal is to fix management practices, and then reexamine the relationships presented in this thesis.

Difficulties Encountered

Data on the total quantity of formwork on site was not physically collected in the field. This was difficult to determine since formwork was constantly being moved around site and from project to project. The total quantity of formwork available on each site was determined by subtracting the cumulative quantity stripped from the cumulative quantity erected on a daily basis. The greatest daily difference was used as the total inventory available. However, these values were checked against first hand field observations and appeared to be realistic.

Evaluation of the four case study projects revealed that three out of four projects were very disrupted. The disruptions involved with the projects limited the number of good productivity performance days. The disruptions associated with piers and pier caps required the scope of the lead-time, crew, and inventory sizing to be limited to footings and abutment walls. Further, as discussed above, the management on these projects has potentially caused the findings from the observed projects to be skewed.

Implementation of Tools

The following section outlines the three areas that contractors should consider when utilizing the tools developed in this thesis. These areas focus on planning, data collection, and execution of the work.

Planning

Crew size, lead-times, and inventory need to be planned before a project ever begins. The first step in determining and balancing these three items is to determine a concrete placement cycle time. In determining this cycle time, the manager must allow sufficient time for all the actual steps involved in the cycle. These steps include: erecting formwork, erecting and plumbing reinforcing steel, plumbing formwork, concrete placement, and eventually stripping of formwork. This cycle time is then adapted as the planning lead-time so that the crew can be sized. Now using the previous information, the inventory required on site is determined. These serve as the initial planning figures to ensure adequate resource and work flow.

Collection of Data

The project manager or project engineer should be charged with collecting performance data on the project. The data should include input – output data. In addition to the data, a journal of events should log the successes and challenges on site. The journal should serve as a tool to capture lessons learned to avoid future

pitfalls. The data should be processed to develop a baseline productivity value. The baseline productivity value should be used to help plan subsequent work. Additionally, this project data should be logged in contractors' historical data to help in estimating and planning future projects.

Execution

One key to executing a project is the development of daily work expectations. Initially, historical baseline productivity values for similar projects should be used to assist in planning crew expectations. The historical data should be used until enough field data is collected, as previously discussed, to generate the projects baseline productivity. The baseline productivity is used to develop crew assignments and expectations. Use of this data should serve as an aid to managers helping ensure the appropriate resources are available for the crew to execute the work. Obviously, two-way communication between management, the foreman, and the crew are needed to make this succeed. This should be a tool to help set the stage for the crew to succeed by ensuring the proper resources are available. Each level should have input into what resources are required to realize these expectations.

Conclusion

The interdependency between lead-time, inventory, and crew size can be balanced to optimize the likelihood of good productivity performance. However, there are several other factors that can ultimately lead to poor productivity that need to be actively managed. The balancing of lead-time, inventory, and crew size simply sets the stage for success. Management at all levels needs to be actively involved in the project to avoid the pitfalls of disruptions and poor workforce management. Ultimately, detailed planning and proactive management provides the basis of success.

The concepts presented in this thesis can be applied to other aspects of construction. The work expectation tool can be used on any type of work. Obviously, data needs to be collected and analyzed to develop rules of credit, conversion factors, and baseline productivity data. However, once this is done, the quantity of work that one can expect to accomplish on a given day can easily be calculated. Similarly, balancing crew size, lead-time, and inventory can be applied to other areas. However, this will require future research into the relationships associated with the type of work.

Recommendations for Future Research

This thesis presented a tool for balancing crew size, lead-times, and inventory to optimize productivity. The planning figures presented should be verified by continued research in this area. An assortment of projects should be studied.

Ideally, well-managed projects should be used to confirm or deny the results with particular attention on the lead-time, inventory, and daily productivity relationships. Further, projects that use different cycle times should be used to help examine the impact of lead-times and inventory.

Research needs to be extended beyond footings and abutment walls. The data used to develop the lead-time, crew, and inventory sizing tool was limited to construction of footings and abutment walls. Data should be collected to capture sufficient information on pier columns and pier caps to develop an overall planning system for bridge construction.

This thesis presented the concept of expected productivity. Further research is needed to verify the expected component productivities. Additional research and data will contribute to the accuracy of the component productivities.

GLOSSARY

Lead-time – A time period or quantity of work between trades, crews, or tasks. It is a management tool used to provide a constant amount of work to a crew despite visibilities that occur in the workflow.

Inventory – The quantity of materials or partially completed work awaiting further processing. (Tommelein, 1998)

Conversion Factor – The ratio of the unit rate of an item compared to the unit rate of the standard item. This value reflects how much easier or harder an item is to install versus the standard item. (Thomas, 2000)

Productivity - Productivity is defined as the quantity of hours expended divided by the quantity of work accomplished. This is also often referred to as the unit rate. Lower values indicate better productivity (Thomas and Oloufa, 1995)

Baseline Productivity - The baseline productivity is the best performance that a crew can achieve given the complexity of the work . It the productivity achieved on the top 10% of the days with the highest output. The total quantity of workhours is divided by the total quantity of work installed.

Cumulative Productivity - This is the productivity that the crew actually achieved for a particular job. It is calculated by dividing the total number of workhours expended by the total quantity of work installed. Cumulative productivity is a measure of both the job complexity and the work environment.

Expected Productivity - Expected productivity is the baseline productivity one should expect to achieve on a project based upon the components contained in the project's baseline subset. Expected productivity is weighted average of the respective component productivities contained with in the baseline subset. It should be nearly the same as the actual projects baseline productivity.

Project Management Index (PMI) / Project Waste Index (PWI) - PMI is a dimensionless measure of how well management controlled the factors that influence productivity. It reflects work environment's influence on productivity. PMI is calculated by the following equation:

$$\text{PMI} = \frac{\text{Cumulative Productivity} - \text{Baseline Productivity}}{\text{Expected Productivity}}$$

Percent Plan Complete - The percentage of a weekly work plan that is accomplished by a crew. Percent plan complete is a measure of workflow reliability. (Ballard, 1999)

Cycle Time – This is the time required for a piece of material or work to traverse the flow or process. (Koskela, 1992)

RAW DATA

Project	Workday	WorkHrs Fmwk & Concrete	Erect 0.75	Plumb 0.15	Strip 0.10	Pour 1.00
24 & 25	1	50	479.20	0.00	1198.00	0.00
24 & 25	2	70	718.80	1198.00	0.00	0.00
24 & 25	3	0	0.00	0.00	0.00	0.00
24 & 25	4	70	0.00	0.00	0.00	70.00
24 & 25	5	50	0.00	0.00	1198.00	0.00
24 & 25	6	50	958.40	0.00	0.00	0.00
24 & 25	7	60	239.60	599.00	0.00	0.00
24 & 25	8	50	0.00	599.00	0.00	0.00
24 & 25	9	48	0.00	0.00	0.00	70.00
24 & 25	10	24	0.00	0.00	119.80	0.00
24 & 25	11	12	0.00	0.00	539.10	0.00
24 & 25	12	50	0.00	0.00	539.10	0.00
24 & 25	13	50	1198.00	239.60	0.00	0.00
24 & 25	14	50	0.00	479.20	0.00	0.00
24 & 25	15	77	0.00	479.20	0.00	70.00
24 & 25	16	28	0.00	0.00	119.80	0.00
24 & 25	17	60	448.00	448.00	0.00	0.00
24 & 25	18	60	0.00	0.00	280.00	0.00
24 & 25	19	60	0.00	0.00	114.50	0.00
24 & 25	20	60	816.00	408.00	0.00	0.00
24 & 25	21	70	200.00	408.00	0.00	30.00
24 & 25	22	0	0.00	0.00	0.00	0.00
24 & 25	23	0	0.00	0.00	0.00	0.00
24 & 25	24	50	264.00	200.00	0.00	0.00
24 & 25	25	50	0.00	264.00	0.00	0.00
24 & 25	26	70	0.00	0.00	488.00	30.00
24 & 25	27	20	0.00	0.00	264.00	0.00
24 & 25	28	40	512.00	0.00	0.00	0.00
24 & 25	29	50	144.00	656.00	0.00	29.00
24 & 25	30	30	432.00	216.00	0.00	0.00
28 & 29	1	64	292.00	87.60	0.00	0.00
28 & 29	2	27	388.00	116.40	0.00	0.00
28 & 29	3	80	956.00	286.80	0.00	0.00
28 & 29	4	80	184.00	55.20	0.00	0.00
28 & 29	5	80	0.00	509.60	0.00	0.00
28 & 29	6	32	0.00	254.80	0.00	0.00

Project	Workday	WorkHrs Fmwk & Concrete	Erect 0.75	Plumb 0.15	Strip 0.10	Pour 1.00
28 & 29	7	64	0.00	509.60	0.00	0.00
28 & 29	8	165	0.00	0.00	0.00	570.00
28 & 29	9	70	0.00	0.00	0.00	80.00
28 & 29	10	70	552.00	0.00	0.00	10.00
28 & 29	11	77	0.00	0.00	0.00	250.00
28 & 29	12	32	0.00	0.00	0.00	83.00
28 & 29	13	120	1500.00	846.00	0.00	0.00
28 & 29	14	70	1032.00	462.00	0.00	0.00
28 & 29	15	70	0.00	888.00	0.00	0.00
28 & 29	16	70	0.00	888.00	0.00	0.00
28 & 29	17	90	0.00	0.00	0.00	0.00
28 & 29	18	70	404.00	161.60	0.00	0.00
28 & 29	19	246	0.00	242.40	0.00	780.00
28 & 29	20	130	864.00	88.00	4760.00	0.00
28 & 29	21	120	576.00	776.00	0.00	0.00
28 & 29	22	120	0.00	0.00	0.00	94.50
28 & 29	23	114	1008.00	1008.00	1000.00	30.00
28 & 29	24	220	2080.00	1168.00	824.00	0.00
28 & 29	25	190	2569.00	3145.00	0.00	0.00
28 & 29	26	130	856.00	1340.00	164.00	0.00
28 & 29	27	23		0.00	0.00	0.00
28 & 29	28	240	88.00	516.00	1827.00	136.00
28 & 29	29	149	1024.00	88.00	170.50	0.00
28 & 29	30	220	1901.25		2048.00	0.00
28 & 29	31	220	1024.00	1192.11	844.00	0.00
28 & 29	32	210	0.00	1974.63	0.00	0.00
28 & 29	33	190	1076.00	690.51	1152.00	90.00
28 & 29	34	290	1044.00	20.00	1024.00	630.00
28 & 29	35	250	1024.00	2048.00	1704.28	0.00
28 & 29	36	104	0.00	0.00	0.00	150.00
28 & 29	37	70	792.00	0.00	2048.00	0.00
28 & 29	38	80	792.00	0.00	0.00	0.00
28 & 29	39	180	0.00	2048.00	0.00	90.00
28 & 29	40	130	0.00	0.00	1536.00	150.00
28 & 29	41	130	0.00	0.00	3891.20	
28 & 29	42	80	600.00	2648.00	204.80	
28 & 29	43	140	960.00	480.00	0.00	70.00
28 & 29	44	160	1674.64			
28 & 29	45	80				137.00
28 & 29	46	70				80.00
28 & 29	47	120	1304.00	1744.00		
28 & 29	48	130		800.00		
28 & 29	49	150				205.00
28 & 29	50	150	420.00		2728.00	

Project	Workday	WorkHrs Fmwk & Concrete	Erect 0.75	Plumb 0.15	Strip 0.10	Pour 1.00
28 & 29	51	80	1646.00	823.00		
28 & 29	52	100	746.00			
28 & 29	53	130		1280.00		115.00
28 & 29	54	70				69.00
28 & 29	55	50	840.00	576.00		
28 & 29	56	40	711.00			
28 & 29	57	40			728.00	
Logan Br.	1	0	0.00	0.00	0.00	
Logan Br.	2	80	1184.00	592.00	0.00	
Logan Br.	3	80	1184.00	1184.00	0.00	
Logan Br.	4	80	880.00	592.00	0.00	
Logan Br.	5	70	384.00	1264.00	0.00	
Logan Br.	6	0				
Logan Br.	7	50	168.00	0.00	0.00	
Logan Br.	8	42	0.00	168.00	0.00	
Logan Br.	9	60	0.00	0.00	0.00	
Logan Br.	10	42				75.00
Logan Br.	11	25	608.00	0.00	1056.00	
Logan Br.	12	120	832.00	1440.00	192.00	
Logan Br.	13	90	952.00	952.00	0.00	
Logan Br.	14	110	552.00	552.00	360.00	
Logan Br.	15	70				71.00
Logan Br.	16	110	1600.00	1600.00	0.00	
Logan Br.	17	121	864.00	0.00	0.00	
Logan Br.	18	220	0.00	864.00	0.00	
Logan Br.	19	150				290.62
Logan Br.	20	110	0.00	0.00	2464.00	
Logan Br.	21	70	0.00	0.00	0.00	
Logan Br.	22	100	192.00	192.00	0.00	
Logan Br.	23	100	372.00	372.00	0.00	
Logan Br.	24	70	408.00	408.00	0.00	
Logan Br.	25	70	408.00	0.00	0.00	
Logan Br.	26	90	37.80	37.80		
Logan Br.	27	100	408.00			
Logan Br.	28	100	1368.00	408.00	0.00	
Logan Br.	29	140	1728.00	864.00	0.00	
Logan Br.	30	100	0.00	864.00	0.00	
Logan Br.	31	40	624.00	400.00	0.00	
Logan Br.	32	130	472.00	472.00	0.00	
Logan Br.	33	110	0.00	224.00	0.00	
Logan Br.	34	80	432.00	432.00	2680.00	
Logan Br.	35	80	1496.00	0.00	1188.00	
Logan Br.	36	100	192.00	1688.00	0.00	

Project	Workday	WorkHrs Fmwk & Concrete	Erect 0.75	Plumb 0.15	Strip 0.10	Pour 1.00
Logan Br.	37	60	26.00	26.00	0.00	99.60
Logan Br.	38	110	644.00	0.00	0.00	
Logan Br.	39	100				56.10
Logan Br.	40	200				461.00
Logan Br.	41	120	0.00	284.00	0.00	
Logan Br.	42	100	384.00	384.00	0.00	
Logan Br.	43	150	64.00	360.00	1728.00	
Logan Br.	44	110	1568.00	0.00	0.00	
Logan Br.	45	40	1224.00	840.00	0.00	
Logan Br.	46	100	552.00	250.00	0.00	
Logan Br.	47	100	888.00	302.00	0.00	
Logan Br.	48	91	0.00	804.00	224.00	
Logan Br.	49	50	768.00	84.00	440.00	
Logan Br.	50	40				39.00
Logan Br.	51	80	42.00	1056.30	0.00	
Logan Br.	52	132	1283.00	0.00	345.00	
Logan Br.	53	100	186.00	0.00	0.00	
Logan Br.	54	360	0.00	0.00	0.00	667.00
Logan Br.	55	120	100.00	0.00	0.00	
Logan Br.	56	60	20.00	581.00	0.00	
Logan Br.	57	110	37.80	37.80		
Logan Br.	58	100	0.00	0.00	704.00	
Logan Br.	59	90	0.00	1776.00	128.00	
Logan Br.	60	80	0.00	0.00	590.00	
Logan Br.	61	80				
Logan Br.	62	100				110.00
Logan Br.	63	90	400.00		2160.00	
Logan Br.	64	90	666.75			
Logan Br.	65	90	160.00			37.00
Logan Br.	66	99	592.00			
Logan Br.	67	44			576.00	
Logan Br.	68	108	1776.00			
Logan Br.	69	90	396.00			
Logan Br.	70	99	204.00	1776.00		
Logan Br.	71	80				68.00
Logan Br.	72	81	672.00	24.00		
Logan Br.	73	72	390.00			
Logan Br.	74	56				110.00
Logan Br.	75	72	1324.00			
Weaver Hill	1	86	922.00	405.00	0.00	26.0
Weaver Hill	2	78	1061.00	325.00	0.00	24.0
Weaver Hill	3	70	176.00	552.00	1448.00	0.0
Weaver Hill	4	25	0.00	552.00	0.00	0.0
Weaver Hill	5	80	676.00	0.00	1104.00	0.0

Project	Workday	WorkHrs Fmwk & Concrete	Erect 0.75	Plumb 0.15	Strip 0.10	Pour 1.00
Weaver Hill	6	120	0.00	436.00	702.00	0.0
Weaver Hill	7	120	0.00	240.00	0.00	47.0
Weaver Hill	8	100	480.00	0.00	384.00	0.0
Weaver Hill	9	80	648.00	0.00	288.00	69.0
Weaver Hill	10	90	888.00	0.00	684.00	0.0
Weaver Hill	11	90	422.00	0.00	0.00	0.0
Weaver Hill	12	70	0.00	0.00	0.00	57.5
Weaver Hill	13	120	576.00	212.00	888.00	0.0
Weaver Hill	14	104	178.00	754.00	0.00	0.0
Weaver Hill	15	80	0.00	212.00	0.00	73.0
Weaver Hill	16	20	0.00	0.00	412.00	0.0
Weaver Hill	17	50	0.00	0.00	948.00	0.0

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